War Shelters Inspired by Nature:

Design Model for Contingency Troop Housing Based on Biomimetic Principles

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May 2011

Submitted towards the fulfillment of the requirements for the Doctor of Architecture Degree

School of Architecture
University of Hawai'i

Doctorate Project Committee
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We certify that we have read this Doctorate Project and that, in our opinion, it is satisfactory in scope and quality in partial fulfillment for the degree of Doctor of Architecture in the School of Architecture, University of Hawai'i at Mānoa.

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This doctorate project is dedicated to all the men and women who have served or currently serving the United States Armed Forces. Your dedication, love, and sacrifice for our country are more than words can express. Thank you for your service!

ABSTRACT

Hundreds of thousands of U.S. military are serving in the Middle East in support of the War on Terrorism. Aside from the danger that soldiers have to face every day, they are challenged by the harsh desert climate conditions, which greatly affect their quality of life. The only means of thermal comfort there is largely governed by Heating, Ventilation, and Air Conditioning (HVAC) systems that are powered by fossil fuels, one of the greatest contributors to global warming. Biomimicry, a new discipline that studies nature's best biological ideas and then imitates these forms, processes, systems, and strategies to solve human problems, is the recommended approach to sustainable design. The purpose of this project is to develop a design model that offers comfort and protection for troop shelters based on biomimetic principles.

The final design proposal is a synthesis of three important aspects of the research: the recognition of global warming challenges, the confinement of military standards, and the interpretation of nine biomimetic design principles extracted from the study of desert plants and animals. A detailed outline of the biomimetic design principles along with a clear understanding of the different phases of contingency construction formalized the initial context of the new war shelter. The final design example is a burrowed and bermed living space that is sheltered by a modular panelized roof and wall system.

Through a combination of building and model simulation and a comprehensive comparative analysis that factors in every numerous variables of design, one can conclude that a low greenhouse gas emission design model for troop shelters that provides comfort and protection can be achieved by using biomimetic principles. The principle of burrowing in particular demonstrated the strongest improvement in both the thermal comfort and protection in a desert contingency environment. Meanwhile, the range and level of improvements in the comfort and protection need to be further supported by scientific and quantitative data.

Biomimcry is a relatively new discipline and is open to many different interpretations. Unlike other design approaches, biomimicry is research and scientific driven, which means it is a less subjective and more valid approach to green design solutions. The design example provided is not the ultimate solution for the improvement of war shelters in a contingency environment. It merely serves as an experiment and exploration of the many possibilities that nature can offer to improve the comfort and protection housing in a desert environment throughout the world.

PERSONAL STATEMENT

One of the greatest lessons that I learned in life is plan for the unplanned. I truly believe that everything in life happens for a reason. Never in my teenage life have I thought about joining the military, deploying to Iraq, or even becoming a veteran. Becoming an architect is all that I have ever dreamed of doing since childhood. In the spring of 2003, I entered the School of Architecture doctoral program at the University of Hawaiʻi, ready to pursue my dream as an architect. That same year, I joined the Hawaiʻi Army National Guard for a number of personal reasons, which led into many obstacles throughout my studies in architecture. Being a soldier has thus very much been a part of my life while studying architecture. It is because of these unique personal experiences in the military along with my passion for architecture that resulted in my interest in the exploration of this doctorate project.

In the summer of 2007, I was called to duty to serve in Iraq. Living and working there for ten months made a very deep impression on me regarding climate change. The weather there goes from extreme hot to extreme cold, and without air conditioning, living there for an extended period of time would have been absolutely unbearable.

Serving in Iraq reminded me that our global environment is changing constantly. Each summer seems to be hotter and drier, and each winter seems to be longer and colder. Climate change is becoming one of the leading challenges in architecture. Designers from around the world are looking for new, innovative, and efficient ways to maintain or improve the level of comfort level in our living and work spaces.

Biology is one of my favorite subjects in school. How life and living organisms evolved and sustained themselves in the natural environment is something that always fascinates me. Animals and plants have learned to adapt and thrive in the environments in which they live. Even in an extreme environment like the desert, life is abundant. Therefore, understanding how nature functions and incorporating there life principles in design is an appropriate means of creating solutions that responsive to the changing conditions of our planet. The marriage between nature and architecture is the foundation of this doctoral project. As a member of the military, and in honor of all the men and women who have volunteered to serve our country, I want to take this opportunity to design a war shelter inspired by nature that will improve the comfort and protection of housing for troops in a desert contingency environment.

PREFACE

Since the tragic events of September 11, 2001, a significant number of soldiers have been mobilized to the Middle East in support of Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF). Though the numbers of soldiers in Iraq have decreased in recent years, troops continue to be rotated to the Middle East. As the United States continues to fight the Global War on Terrorism, soldiers have to face the reality of being deployed throughout the world. Depending on the frequency and extent of each deployment, one of the major factors that affect the quality of life for soldiers is housing conditions. Although war shelters have improved considerably through time, soldiers are challenged by climate, which affects their thermal comfort and health. To maintain a level of indoor comfort, soldiers are dependent on air conditioning for heating and cooling. Air conditioning increases electricity use, which in turn amplifies our dependency on fossil fuels and further aggravates the problem of global warming. In the long run, air conditioning is not the ultimate solution to climate change and living comfort.

Biomimicry (from bios, meaning "life", and mimesis, meaning "to imitate") is a design principle that seeks sustainable solutions to human initiated problems like global warming by consulting and emulating nature's time-tested patterns and strategies. Simple animals, plants, and microbes existed on the planet long before human beings. Throughout the various stages of climate change on Earth, they have learned to adapt and fit into the changing environment. More importantly, they have not fostered global warming. What can nature teach us?

Recognizing the issue of climate change and the possibility of U.S. forces being deployed to any part of the world at any given period of time, the purpose of this research and design project is to explore a possible design model based on biomimicry that will offer comfort and protection for troops in a desert contingency environment. Through historical research and assessment, present condition observation, exploration of biomimetic principles, qualitative analysis, and design modeling and simulation, an alternative approach to traditional environmental control systems can be realized. Our dependency on fossil fuels will be lower and the impact of climate change minimized.

PART I: BACKGROUND

1. PERSONAL EXPERIENCE + INSPIRATION

1.1 Experiences in Iraq

From August 2007 to June 2008, I was deployed to Tallil, Iraq, an airbase located near the city of An Nasiriyah. Although it was only a ten-month development, it was a life-changing experience for me, in part because I had never lived in such a severe climate. Living in a desert environment made me wonder about how housing should be design under such harsh climate conditions. The temperature there can get as high as 120˚F in July and August to below freezing in January and February. Living shelters there consist of tents and shipyard containers protected by only sandbags and concrete slabs. I have never been to a place so hot in the morning and afternoon, with unexpected periodic of sand storms, and freezing temperatures with high winds at night. At that time and place, air conditioning and living in a container was perceived as a life saving combination. The creation of air conditioning (AC) made living in hot regions like Iraq tolerable. Regardless of how extreme the temperature is outside, AC is able to maintain the level of comfort within the space. However, AC is energy demanding. With the on-going deployments to the Middle East, the demand for AC continues to rise and the impact of global warming continues to amplify. Are there alternative ways for thermal regulation? How can we reduce our dependency on fossil fuels? Living in a desert for ten months really left a deep impression on me. As a designer and soldier, I feel the urge to address this problem and explore ways to save our planet from further deterioration. We are not only fighting a War on Terrorism, but a war on climate change.

1.2 Design Inspired by Nature

Since the early nineteenth century, architects and designers have looked to biology for inspiration. They sought to not only imitate the forms and adaptations of plants and animals, but also to grasp a deeper understanding of biological processes and evolution in nature in order to derive new models and methods in design.[1] Due to growing concern about the environment and the rise of green and sustainable design, architects are focusing on organic forms and systems in order to create designs in harmony with nature. Buildings, for instance, are often organized in a bilateral symmetrical layout similar to that of an animal's structure and form, and many architectural ornaments are borrowed from plants and animals. Spiral capitals,

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[1] Steadman, Philip. *The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts*. New York: Routledge, 2008.

spiral staircases, spiral columns, and spiral towers are all examples inspired by the study of DNA and similar spiral and radial symmetries found in nature.[2]

Life in nature has evolved in many ways to adapt to the environment harmoniously. Through billions of years of evolution, plants, animals, and other living creatures have learned to better adapt to changes on this planet. Therefore, there must secrets in nature that we can emulate to improve the way we live on the planet more sustainably and harmoniously. Biomimicry is a design principle that seeks solutions in nature. How can the biological principles of a plant or animal help to naturally or mechanically cool, heat, and ventilate a space?

Animal shelters serve the same fundamental purpose as human shelters; that is, to create a protected home. Animal constructions also meet the same kinds of functional needs as human architecture such as structure, ventilation, and space planning. Many of the structural and functional achievements of animal construction developed through millions of years of evolution and adaptation are perfect examples of flawless responses to life-changing conditions. Moreover, many animal shelters meet our goals of creating more efficient and sophisticated designs by minimizing the use of material and labor. Spiders for instance eat their building structures in order to reuse their building materials. So what can we learn from the ecological adaptations of animal buildings?

Nature is a remarkable inventor that has already produced through natural selection all kinds of systems, structures, and materials that best fit in their respective contexts. Therefore, it is up to us to identify and understand these products and methods and to apply them to our technologies and designs.

1.3 Biomimicry

Nature is all around us, whether we live in an urban or rural setting. The beauty of nature and what we see today is the result of a very elaborate and sophisticated process. Throughout history of mankind, animals, plants, and organisms have evolved to live in the changing environment. Due to increasing concerns regarding global warming and increasing interest in sustainable design, many scientists and designers are moving in a new direction known as "biomimicry." *Bios* means life and *mimesis* means to imitate. Biomimicry is a new

[2] Hersey, George. *The Monumental Impulse: Architecture's Biological Roots*. London: The Mit Press, 2001.

science that studies nature's models and then takes inspiration from these designs and processes to solve human problems.[3]

After 3.8 billion years of evolution, nature has learned and transformed. In the process known as natural selection, weak organisms died while stronger ones lived and evolved and new organisms emerged. Nature is therefore a good resource for design professionals who can measure and extract solutions and adapt them for human intervention. As we learn more about nature, it also becomes our mentor, guiding us to a new way of viewing and valuing it. Biomimicry is "not based on what we can extract from nature, but on what we can learn from her.[4] What we see in nature today is what works, what lasts, and what we should be doing to make our systems environmentally friendly, and ecologically, socially, and economically sustainable for the generations to come.

In each of the case studies discussed in *Biomimicry: Innovation Inspired by Nature*, Janine Benyus, a natural sciences writer and innovation consultant, and researchers from different areas, share how nature can be used as a model to help create ingenious solutions to human problems. Examples include solar cells inspired by photosynthesis in leaves; waterproof fibers five times stronger than steel that were developed after analyzing spider silk; cancer cures drawn from chimpanzees; and perennial grains inspired by tall grass. The book demonstrates how innovations inspired by nature can generate more efficient energy, shape the way we make things to better fit their functions, and help to heal millions of people around the globe who are suffering from disease. Benyus believes that the reason we are facing many of our current dilemmas is not because the answers do not exist, but because we simply have not been looking in the right places. She suggests that it is time to step away from the city center, walk in the forest, and let nature lead the way.

Nature has shaped systems over billions of years that work in harmony with each other and our challenge is to learn how to honor them and be inspired by their truth to create new cultural values and systems.[5] It is important to recognize that Earth's resources are not unlimited and that as the population grows, living space becomes scarce as well. Therefore, in order to extract from nature, we need to remind ourselves that we cannot conduct business like we used to, constantly using materials and resources like they are endless. Without human

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[3] Benyus, Janine M.. *Biomimicry: Innovation Inspired by Nature*. New York: Harper Perennial, 2002.
[4] Ibid
[5] Ibid p.238.

intervention, nature could have sustained itself. Benyus offers “ten commandments” based on organisms in a mature ecosystem as means of finding harmony with nature: use waste as a resource; diversify and cooperate to fully use habitats; gather and use energy efficiently; optimize rather than maximize; use materials sparingly; don't foul nests; don't draw resources down; remain in balance with the biosphere; run on information; and shop locally.[6]

Biomimicry can be used as a guiding principle for the achievement of a better habitat for human beings. By analyzing nature’s processes and systems, architects can design spaces that are more hospitable, functional, and in harmony with nature. An ever-changing evolutionary process is maintained in nature so that inefficient systems disappear, while the efficient characteristics prevail and develop as the environment changes. When inspired by these models, we can take advantage of this process of improvement and create better designs.

1.3.1 Principles of Biomimcry

According to Janine Benyus, there are nine underlying principles in nature from which human beings should learn:

1. Nature runs on sunlight.
2. Nature uses only the energy it needs.
3. Nature fits form to function.
4. Nature recycles everything.
5. Nature rewards cooperation.
6. Nature banks on diversity.
7. Nature demands local expertise.
8. Nature curbs excesses from within.
9. Nature taps the power of limits.[7]

Each of these principles demonstrates how nature is in harmony with the environment. There is also strong evidence of human activities as distinct from nature. For instance, we use metals, which nature never does; we make things out of many components, each of which is homogenous, whereas nature makes things out of fewer components that vary internally; we design for stiffness, nature designs for strength and toughness; our mechanisms have rigid pieces moving on sliding contacts, nature bends, twists, and stretches; our engines are mostly

[6] Ibid
[7] Ibid

rotary or expansive while nature's are mostly sliding or contracting; and nature often uses diffusion, surface tension, and laminar flow whereas we often use gravity, thermal conductivity, and turbulence.[8]

Nature has a lot to offer. Through an in-depth study of how plants and animals adapt to their changing environments, I truly believe an innovative design solution will emerge that will provide U.S. soldiers who have dedicated their lives to serve and fight for the freedom we often take granted a more habitable space in a desert contingency environment.

[8] Ibid.

2. PROJECT STATEMENT

2.1 Project Statement

This doctoral project focuses on how the principles of biomimicry can be applied to a design model that offers comfort and protection for troops without dependency on artificial mechanical systems or air conditioning powered by fossil fuels. Having personally experienced living in a severe climate environment where the temperature is either extreme hot or extreme cold; and the only means of comfort is air conditioning, a large amount of energy is consumed and more greenhouse gas is emitted to the atmosphere. Air conditioning increases the demand for fossil fuels, which fosters global warming and can potentially cause major health problems. This project is intended to address the comfort and protection provided by troop shelters in a desert contingency environment while also recognizing the continued impact of climate change on average temperature rise. The project is center in the development of a new war shelter; therefore, military standards of construction and modularity are important factors to consider in the design process.

Animals, plants, and microbes have undergone billions of years of change in form, system, and/or structure to become what they are today. The desert biome is known for its extreme climate, yet many living organisms including plants, insects, and animals survive there. Desert plants have many different ways of adapting to extreme dry habitats. Some use physical structures while others depend on behavioral mechanisms for survival. Based on the principles of biomimicry, a variety of desert plants and animals were studied in search of a form, structure, or system that can be mimicked and adopted to a design model that offers comfort and protection for troops.

2.2 Hypothesis

A design model for troop shelters that provides comfort and protection can be achieved by using biomimetic principles that minimize greenhouse gas emissions as an alternative approach to traditional environmental control systems.

PART II: RESEARCH

3. INTRODUCTION

Thousands of U.S. soldiers continue to be mobilized in support of the missions in Iraq and Afghanistan. For many, it might be their fourth or fifth deployment. Being away from home and living in a danger zone is challenging, but what makes this experience even more difficult for deployed soldiers is the harsh climate. Soldiers depend heavily on air conditioning for their comfort, but this is a large contributor to greenhouse gas emissions and global warming. This research seeks alternative shelters for soldiers that are more environmentally friendly.

Life in the desert is not impossible. There are many animals and plants that have thrived in this extreme environment for millions of years. Biomimicry, a new discipline that studies nature's best developed ideas and then imitates these designs and processes to solve human problems might offer means of providing comfort and protective housing for soldiers who are deployed to hot and dry desert environments.

What are the current living facilities and conditions for soldiers in Iraq? How do current structures compare to past ones? How are greenhouse gas emissions, particularly in respect to air conditioning, affecting global warming? Is there evidence that proves the benefits of practicing biomimicry? What are some classic examples? The purpose of the research section is to answer some of these questions and to convince readers that this exploration is valuable and meaningful for the future of green designs.

4. GLOBAL WARMING + CHALLENGES

4.1 Global Warming

Global warming is an average increase in the temperature of the atmosphere near the earth's surface and in the troposphere, which can contribute to changes in global climate patterns. Global warming can result from a wide variety of causes, both natural and human induced.[9] Historically, natural factors such as volcanic eruptions affected the earth's climate. However, since the Industrial Revolution, human activities such as the burning of fossil fuels and significantly increased deforestation have caused substantial emissions of greenhouse gases into the atmosphere. As the concentration of greenhouse gases in the atmosphere increases, the composition of the atmosphere changes and this in turn changes the earth's climate.

Greenhouse gases are essential to life because they keep the planet's surface warm enough for life, but as the concentration of these gases continues to increase, Earth's temperature will exceed past levels. According to National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) data, Earth's average surface temperature has increased by about 1.2 to 1.4˚F in the last 100 years. If greenhouse gases continue to increase, climate models predict that the average temperature on the earth's surface could increase from 3.2 to 7.2˚F above 1990 levels by the end of this century.[10] Scientists are certain that human activities are the cause, and the increased concentration of greenhouse gases will not only change the planet's climate, but also rainfall patterns, snow and ice cover, and sea levels, all of which will significantly impact our living patterns and environment.

Currently, the average increase of temperature caused global warming is at 33˚F (0.7˚C) above pre-industrial levels. According to scientists, in order to avoid dangerous climate change, global warming must be kept under 35.6˚F (2˚C) above pre-industrial levels. If global warming reaches 37.4˚F (3˚C), disastrous climate change will occur on earth. In a 2 to 3˚C warmer world, there will be 30% less snowpack, and 60% less water content in the snowpack; the number of acres burned by forest fires in the west are expected to double or even quadruple; coral reefs, home to 25% of all marine species, will begin to disappear; 25% of all plant and animal species

[9] "Basic Information | Climate Change | US EPA." US Environmental Protection Agency. http://www.epa.gov/climatechange/basicinfo.html (accessed April 1, 2009)
[10] Ibid

on earth will become extinct by 2050; and millions of people living along coastlines across the globe will be affected by just one meter of sea level rise.[11]

4.2 Greenhouse Gas Emissions

Unfortunately, we cannot undo what has been done in the past, but is there anything we can do now to prevent or mitigate the further impact of global warming? Based on the 2009 U.S. Greenhouse Gas Inventory Report provided by the U.S. Environmental Protection Agency (EPA), carbon dioxide (CO2) is the primary gas emitted from fossil fuel combustion and represents the largest share of U.S. greenhouse gas emissions.[12] Energy burned to run cars and trucks, heat homes and businesses, and power factories is responsible for about 80% of global carbon dioxide emissions, about 25% of U.S. methane emissions, and about 20% of global nitrous oxide emissions. In the U.S., our energy-related activities account for three-quarters of our human-generated greenhouse gas emissions, mostly in the form of carbon dioxide emissions from burning fossil fuels. More than half the energy-related emissions come from large stationary sources such as power plants while about a third comes from transportation. Industrial processes (such as the production of cement, steel, and aluminum), agriculture, forestry, other land use, and waste management are also important sources of greenhouse gas emissions in the United States.[13] Therefore, the most immediate way to mitigate the impact of global warming is to reduce greenhouse gas emissions by reducing the high demand for energy and seeking alternative renewable energy solutions.

4.3 Climate Change and Challenges

It is not a question of whether the earth's climate will change, but rather when, where, and how much. In a synthesis report published by the Intergovernmental Panel on Climate Change in November 2007, eleven of the last twelve years (1995-200) rank among the twelve warmest years in the instrumental record of global surface temperature (since 1850).[14] Refer to

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[11] "Climate Change, Global Warming, and the Built Environment - 2030 Research Center - Global Impact - A 2°C World." Climate Change, Global Warming, and the Built Environment - Architecture 2030. http://www.architecture2030.org/current_situation/global_impact.html (accessed April 1, 2009).

[12] "US Greenhouse Gas Inventory - 2009 Draft US Greenhouse Gas Inventory Report | Climate Change - Greenhouse Gas Emissions | US EPA." US Environmental Protection Agency. http://www.epa.gov/climatechange/emissions/usinventoryreport.html (accessed April 1, 2009).

[13] "US Greenhouse Gas Inventory - 2009 Draft US Greenhouse Gas Inventory Report | Climate Change - Greenhouse Gas Emissions | US EPA." US Environmental Protection Agency. http://www.epa.gov/climatechange/emissions/usinventoryreport.html (accessed April 1, 2009).

[14] "Climate Change 2007: Synthesis Report". IPCC Plenary XXVII.

Appendix A for locations of significant changes in physical and biological systems data along with surface air temperature changes around the world over the period 1970-2004.

How hot is the planet going to get? Why should this concern us now? There is widespread agreement among climate scientists worldwide that there is clear evidence that climate change is 90% the result of human activity, mainly the burning of fossil fuel-based energy.[15] The paleontological record shows that there have been five massive extinctions in the recorded history of the planet. The most widely known incident occurred at the end of the Cretaceous period, 65 million years ago, when one or more massive meteorites struck Earth, releasing huge quantities of debris into the atmosphere that blocked the sun for years. This resulted in the extinction of 75-80% of species, notably the dinosaurs. However, of all the mass extinctions, the most relevant to the study occurred at the end of the Permian period, 251 million years ago, when a catastrophic chain of events caused the extinction of 95% of all species on Earth. The prime cause was a massive and prolonged period of volcanic eruptions from extensive fractures in the ground. A chain of events also caused massive expulsions of CO2 into the atmosphere which led to rapid warming and plant growth. However, the effect of stripping much of the oxygen from the atmosphere led to a collapse of much of the biosphere. It took the planet 50 million years to return to its previous level of biodiversity. The importance of this evidence lies in the fact that this mass extinction occurred because the planet warmed by 42.8°F (6˚C) over a relatively short period in the paleoclimate timescale. According to the world's top climate scientists on the United Nations Inter-Governmental Panel on Climate Change, Earth could warm by around 42.8°F (6˚C) by the latter part of the century unless global greenhouse gas emissions are reduced by 60% (from their levels in 1990) by 2050.[16]

One of the greatest concerns of global warming is the serious threat to human beings' health. A study by scientists at the World Health Organization (WHO) in 2003 found that 160,000 people die every year from side-effects of global warming, from malaria to malnutrition.[17] That number is expected to double by 2020. Climate change has three different types of health impact: direct, indirect, and migratory. Direct impacts occur through death and injury from heat waves, storms, floods, and drought. Indirect impacts occur through the occurrence of health conditions exacerbated by changing weather conditions, e.g. respiratory

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[15] Smith, Peter. *Architecture in a Climate of Change*. 2 ed. London: Architectural Press, 2005.
[16] Ibid. pg. 7
[17] Crichton, David, Fergus Nicol, and Sue Roaf. *Adapting Buildings and Cities for Climate Change: A 21st Century Survival Guide*. London: Architectural Press, 2005.

diseases. Migratory impacts result from the movement of sources of infection via various carriers within warm climates (e.g., malaria). One of the predicted results of global warming is that there will be greater extremes of weather, which not only means higher temperatures, but also more extensive changes in atmospheric pressure. Research from the University of Lille has indicated that when the pressure falls below 1006 millibars or rises above 1026 millibars, the risk of heart attacks will increase by 13%. The study also showed that a drop in temperature of 50°F (10˚C) will increase the risk of heart attack by the same percentage. The U.K. Department of Health also predicts that by 2020, there will be around 3,000 deaths a year from heatstroke and approximately 10,000 incidences of food poisoning due to climate change. Global warming follow by climate change has a direct health impact and therefore, the issue of greenhouse gas emissions needs to be address immediately before another catastrophic event will happen.

4.4 Building Sector

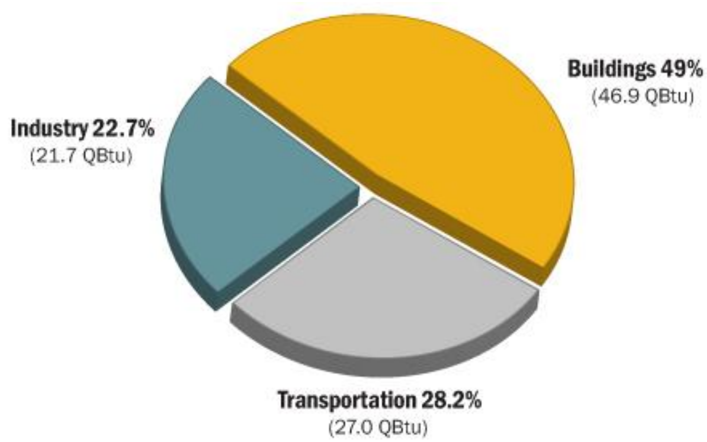

Figure 1: U.S. Energy Consumption by Sector

If reducing energy use and replacing petroleum as an energy source are the keys to mitigating the impact of global warming, on what sector of the economy should we focus? Many people are surprised to learn that buildings are the single largest contributor to global warming. In the most recent U.S. Energy Consumption data charts, the building sector was divided into three parts including industry, commercial, and transportation (Figure 1). To determine the real energy impact of buildings on surrounding climate change and greenhouse gas (GHG) emissions, Architecture 2030 combined these various elements into a single sector called "Buildings." Architecture 2030 is a non-profit, non-partisan, and independent organization established by architect Edward Mazria in 2002 in response to the global warming crisis. 2030's mission is to rapidly transform the U.S. and global building sectors from major contributors of greenhouse gas emissions into a central part of the solution to the global warming crisis. This will require changing the way buildings and developments are planned, designed, and constructed.[18] According to the U.S. Energy Information Administration (EIA), the building sector was responsible for nearly half (46.9%) of U.S. CO2 emissions, transportation accounted for 33.5% of CO2 emissions, and industry accounted for 19.6%(Figure 2).[19] As a result, immediate action in the building sector is necessary to reduce or avoid hazardous climate change in the future.

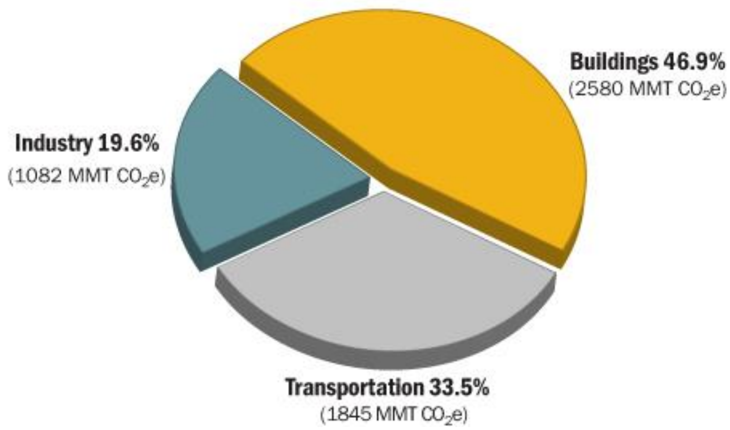

Figure 2: U.S. CO2 Emissions by Sector

In order to prevent disastrous climate change, we need to take action now to reduce greenhouse gas emissions. To maintain or improve our lifestyles without relying on fossil fuels, we need to seek alternative approaches to generating energy.

4.5 Thermal Comfort

What constitutes a comfortable environment and how can we improve space comfort despite climate change? Like all other mammals, human beings are dependent on physiological reactions like sweating, shivering, muscle tension, and changes in blood flow to regulate body temperature. In addition, humans use cultural mechanisms like clothing, shelter, and burning of

[18] "Climate Change, Global Warming, and the Built Environment - About Architecture 2030." Climate Change, Global Warming, and the Built Environment - Architecture 2030. http://www.architecture2030.org/about.php (accessed March 26, 2009).

[19] "Building Sector, Energy, CO2 Emissions - Current Situation - Architecture 2030." Climate Change, Global Warming, and the Built Environment - Architecture 2030. http://www.architecture2030.org/current_situation/building_sector.html (accessed April 1, 2009).

fuel to control temperature so that we can survive in almost all climates. Advances in technologies have led us to be more dependent on these cultural mechanisms for survival. However, these resources are limited. With the impact of climate change on living comfort, how can we revisit the fundamental laws of nature for design inspiration?

Thermal comfort is an important aspect of user satisfaction, which affects the rate and quality of production. Comfort also plays an important factor in determining the amount of energy use in buildings. In order to stay healthy, we have to keep our internal body temperature at an almost constant 98.6°F (37°C). In order to ensure a constant body temperature, the heat produced by the body must, over time, be balanced by the heat lost from it. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers' (ASHRAE) seven point system and Bedford scales of sensation are used to evaluate the extent of comfort in relationship to the degree of temperature; +3 represents hot and -3 represents cold. A field survey among office workers in Pakistan in different indoor temperatures found that adaptive actions such as changing clothing and using air movement can also be used help to control thermal comfort.

4.5.1 Natural Ventilation

Thermal comfort in a building can be achieved by allowing natural ventilation or by the use of artificial mechanical ventilations or air conditioning. The goal is to minimize the need for artificial climate systems by maximizing the use of natural ventilation. Natural ventilation is possible due to the fact that warm air is lighter than cold air and therefore will rise in relation to cold air. Mechanical ventilations involve air flow and movement provisions using fans and air and possibly supply/extract ducts. Air conditioning involves the cooling of the air using refrigeration system.

4.5.2 Air Conditioning

Although air conditioning has been around for over 150 years, it is not the ultimate solution for thermal comfort in hotter regions. Over the course of a century, air conditioning has grown into one of the most powerful industries in the world. However, the problem with air conditioning is that it is a fundamental cause of climate change, the basis of which it was designed to address, creating the paradoxical situation that we face today. Buildings consume over 50% of all energy generated around the world and produce over half of all climate change emissions globally. In the United States, air conditioning alone uses approximately 30-40% of all building-related energy. If the U.S. uses nearly 25% of all the world energy, potentially 5% of all greenhouse gases in the world come from U.S. air conditioning systems alone.[20]

Modern buildings require expensive and unnecessary energy waste in air conditioning. In addition, indoor air quality has been proven to be worse in an air conditioned building than in a comparable, naturally ventilated one. Researchers are finding that the filters, ducts, and plans of air conditioning systems are often filthy, and thus capable of introducing air that is dirtier than the air that would enter if one simply opened a window.[21] This is primarily because many internal ducts are not only seldom cleaned, but also impossible to get at to clean. Thus, the uncleaned filters and long dirty duct runs collect passing toxins and store them until ambient conditions become warmer or more humid, resulting in bad indoor air quality. Rather than trying to find ways to improve the efficiency of air conditioning systems, we need to seek a more environmental friendly way of cooling buildings.

Heating and cooling systems have high energy demands. In addition, the rates of air flow are often higher than simple mechanical ventilation systems and require heavy duty energy-using fans. Systems are also often operated for many hours of the day. An appropriate environmental control strategy would be to eliminate the need for air conditioning.

4.6 Assessment of Global Warming and Challenges

Global warming is changing the world's climate patterns. A large contributing factor to this problem is the increase of greenhouse gas emissions, which is chiefly driven by the building sector. One of the primary means of maintaining comfort against the change of climate is installing heating and ventilation air conditioning units. Soldiers who are currently living in Iraq for instance are heavily dependent on air conditioning for thermal comfort against the extreme climate conditions. Heating and cooling systems require large amounts of energy, which does not solve our current environmental challenge, but rather furthers global warming. Therefore, what are alternate means of providing living comfort without depending on the use of air conditioning?

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[20] Crichton, David, Fergus Nicol, and Sue Roaf. *Adapting Buildings and Cities for Climate Change: A 21st Century Survival Guide*. London: Architectural Press, 2005.
[21] Ibid

5. MILITARY WAR SHELTERS

5.1 History of War Shelters (Past to Present)

Wherever there was war, there were shelters to house the troops. Throughout the history of war, a variety of war shelters have been developed. A new shelter is often the result of a need for improvement based on previous war experiences. By studying the history of war shelters, one can gain a cohesive knowledge about various war shelter modifications. Are these modifications necessary and how beneficial are they to the overall success of their missions? Regardless of how advanced and effective war shelters are today, there is always room for improvement.

The U.S. Military has undergone numerous war shelter modifications. The majority of changes in the design of war shelters were made based on constructability, portability, and flexibility. Due to the large number of troops that may be in the field at one time, the ease of construction plays an important role in ensuring that every soldier has a place to live. Soldiers can be deployed to any part of the world at any given time; therefore, being able to easily transport shelters to and from a place is critical. Meanwhile, it is nearly impossible to create an individual war shelter model for every context, thus the ability to adjust and change each model according to its environment is essential. Lastly, regardless of what the war shelters look like, its general purpose is to provide temporary housing for troops.

In almost every contingency operation, there are multiple options for the construction of the different types of facilities needed at a camp site. These options range from pre-existing structures, tents, pre-engineered metal or fabric buildings, modular buildings, trailer tents, and assembled prefabricated buildings, to manufactured buildings. Each of these models has advantages and disadvantages in the construction process. The understanding of past and present war shelters will provide the background knowledge of what needs improving for future war shelter models and utilize as the base models for comparison of the design model.

5.1.1 Pre-existing Structures

Using pre-existing structures to provide the needed facilities for mission accomplishment is the least time-consuming option. However, the location and accessibility of such facilities may be limited. In addition, the distance of the pre-existing structures from the general command area can be a safety issue. The durability and habitability of the existing structures might also vary. Therefore, prior to settling in a pre-existing structure, an assessment is recommended.

5.1.2 Tent Shelters

5.1.2.1 Shelter Half (Pup Tent)

The shelter half, also known as a "pup tent," was developed during the American Civil War (1861-1865) to protect soldiers in the field. The pup tent continued to be use as temporary shelters for soldiers in the field through the late World War II (Figure 3). Today, the tent is mainly use for soldier training purposes. The tent is approximately 7 feet long, 5 feet wide and 3.5 feet high. Each pup tent is made up of two shelter half pieces that fasten together with a row of buttons or snaps along the ridge line. The tent is then anchored to the ground using poles, ropes, and stakes. The tent can fit a maximum of two people.

The earliest military pup tents were made out of cotton duck material and wooden tent poles. Today, military pup tents are made out of a cotton sateen fabric that is better for protecting soldiers from rain, and the poles are made out of aluminum for ease of transportability. Some commercial pup tents are also made out of nylon, which is resistant to rain.

Figure 3: Pup Tent in WWII

5.1.2.2 Individual Combat Shelter (ICS)

Later, the shelter half was updated to the individual combat shelter designed by Eureka! (Figure 4). Eureka!, a tent division with more than a century of tent and soft shelter experience, is a leading full line tent manufacturer with design capabilities that serve camping, military and commercial canopy/renter markets.[22] Eureka! became a major manufacturing facility since

[22] "Eureka Military Tents." *Eureka Military Tents*. N.p., n.d. Web. 5 Feb. 2010. <http://www.eurekamilitarytent

World War II when tent shelters were in great demand. Made out of lightweight modern materials, the tent is also designed to resist infrared cameras and night vision technology. The new tent is stronger, lighter, portable and more water resistant.

Figure 4: Individual Combat shelter-(Army Combat Uniform Pattern)

5.1.2.3 The Tent, Extendable Modular Personnel (TEMPER)

The Tent Extendable Modular Personnel (TEMPER) tent, a modular, soft-walled, aluminum framed supported tent made of vinyl coated polyester duck cloth that is fire, mildew and water resistant, is designed to grow exponentially and set up in multiple configurations (Figure 5). The most common TEMPER tent configuration is the 32 feet x 20 feet billeting version. TEMPER tents are also used for many other functions, including field feeding, latrines, administrative offices, shops, kitchens, shower/shave units and medical facilities.

The TEMPER tent can be extended in length in 8 feet increments and can be erected in 40 minutes by 5 soldiers (Type IV). The floor area is 640 square feet (Type IV, Personnel -4 sections). Designed to withstand various weather conditions, including desert, tropical and temperate climates, and the TEMPER tents' outer cloth colors (camo green or desert tan) are designed to camouflage with the environment. The TEMPER tent consists of many major components. The major fabric components include the window section, end section, door section and fly. The fly covers the roof of the tent and provides supporting insulation. Utility support for these tents includes electrical service for lighting and convenience outlets and provisions for heating and cooling.

Figure 5: TEMPER tent by U.S. DOD

5.1.2.4 Modular General Purpose Tent System (MGPTS)

A modified version of the original General Purpose Tent (GPT), the Modular General Purpose Tent System (MGPTS) is a larger, modular, pole supported tent that is designed to provide versatile, usable space (Figure 6). The small tent comes in 18 feet wide by 7 feet high and can be expanded by adding additional 18 feet x18 feet modular bay. The MGPTS is based on the concept of a tensioned fabric roof structure that distributes wind, rain, and snow loads from the fabric directly to the support system.[23] The tent is supported by aluminum poles instead of wood, which are lighter and stronger. The outer surface of the tent is coated in a vinyl polyester fabric that is extremely sturdy. The tent also has its own environmental control ducts for heat and air conditioning. A corner arch that goes up the entire perimeter to the top and back down the other side was especially designed to eliminate the support system in the middle of the interior space. Designed to be more flexible and more habitable than the original GPTs, the MGPTS can be used for medical facilities, troop billeting, command and control, field service support, emergency/disaster relief, maintenance functions and storage. The windows and doors are designed to roll-up or down. Available in three sizes: small, medium, and large, the tent can be erected between 27-67 minutes depending on the size of tent and number of people building the tent.

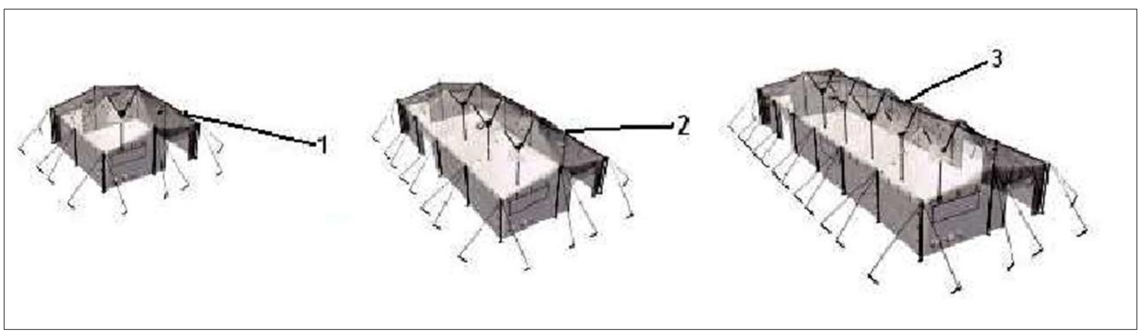

Figure 6: MGPTS 1. Small, 2. Medium 3. Large)

5.1.2.5 Deployable rapid assembly shelter (DRASH)

Part of military training and combat operations for more than 20 years**,** DRASH military shelters are considered worldwide to be the most proven, tested and trusted infrastructures in

[23] "Outdoor Venture Corporation - MGPTS Military Pole and Tension Tents." Outdoor Venture Corporation - Military Tent Manufacturer. http://www.outdoorventure.com/tent_systems/mgpts.html (accessed February 7, 2010).

use by the military today.[24] DRASH Shelters are available in 45 models ranging in size from 109 – 1,250 square feet (Figure 7). DRASH Shelters are also fully customizable and can be interconnected to increase or decrease an overall structure's footprint.

The basic DRASH design consists of a frame with two pre-attached covers and a ground cover. This means that setting up this portable shelter does not require special tools or dealing with loose parts. The pre-attached double layer of fabric also provides a naturally temperature-controlled environment even without environmental support. The shelter's frame is comprised of pairs of struts that connect at key points in the framework called hubs. These hubs allow the shelter to be pushed up and out with no locking devices for quick set up or take down.

The DRASH Shelter's extreme durability can mostly be credited to the advanced technology of its various components. Titanite®, which makes up most of the shelter's frame, is an aerospace composite with superior structural properties that have been independently tested to be 270 percent stronger than aluminum for the same diameter and cross sectional area. XYTEX® is a specially coated fabric that is fire retardant, mildew resistant, water repellent and highly resistant to abrasion and ultra violet rays.

All cover fabrics include blackout in the visual and near infrared spectrum and meet mil-standard requirements for soft-walled shelters. Built to withstand the harshest environments, DRASH Shelters have met or exceeded all requirements for rain, wind, temperature, durability, blackout and snow load at the Aberdeen Test Center (ATC) in Maryland.[25]

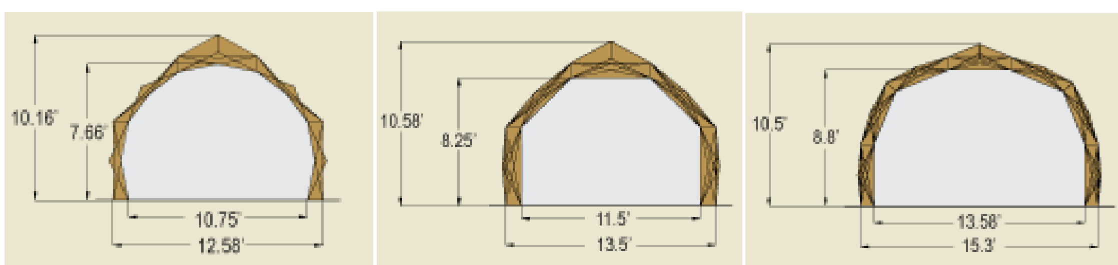

Figure 7: Different DRASH models (L-R: C Series, S Series, XB Series)

5.1.2.6 Modular Shelter System (MSS)

Modular shelter system (MSS), commonly known as clamshell structures are pre-engineered tension fabric building systems developed by Universal Fabric Structure (UFS). MSS

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[24] " Portable US Military Shelters, Rapidly Deployable Military Tents for Sale – DRASH ." Manufacturer of Army Supplies, Military Shelters and Equipment – DRASH . http://www.drash.com/Products/Shelters.aspx (accessed February 3, 2010).

[25] Ibid

are rapidly deployable and can be erected in touch field conditions without special equipment. Based on a lightweight aluminum structure, the MSS is designed in short sections to ensure fast and easy set-up. It requires no foundation and is versatile enough to accommodate various size aircraft, helicopters, and vehicles. The shelter is made up of PVC-coated polyester tensioned fabric that is developed to withstand the most extreme weather conditions. The shelter comes standard with two personnel doors, installation tools, and a complete electrical system. It can be quickly assembled by 6 personnel in less than 24 hours. These structures are known to be durable, versatile, quality shelters, cost effective, and rapidly deployable to many parts of the world for military operations (Figure 8).

Figure 8: Modular Shelter System (MSS) -Clamshell structure

5.1.3 Pre-engineered metal or fabric buildings

5.1.3.1 Nissen Hut

The Nissen hut, designed by Peter Nissen in 1916 is considered to be one of the 100 inventions that shaped the world (Figure 9).[26] While serving as a soldier at a military camp in Ypres, Belgium during WWI, Nissen noticed that there was a lack of simple, easy to build housing for the troops. Inspired by a similar structure that enclosed a hockey rink at Queen's College in Ontario; he began to sketch a series of ideas showing how the principles of that structure could apply to a military hut. The idea of the Nissen hut was not so much about a building that could be dismantled and moved about, but as one idea that could be shipped out in pieces, and erected quickly and easily. The benefit of having a semi-circular structure means that no heavy load-bearing walls are needed and the interior space can be column free. After three major prototypes, input from his superiors, and modifications made after field use, a 16 feet x 17 feet,

[26] Dulken, Stephen Van.*Inventing the 20th Century: 100 Inventions That Shaped the World from the Airplane to the Zipper*. New York City: NYU Press, 2002.

semicircular, steel-arched structure with corrugated metal cladding inside and out was finalized.[27] The Nissen design utilized an interior wall surface of corrugated metal panels with ribs oriented horizontally. The panels were strapped tight to the arch flange by metal cables that run radially over the top. Corrugated metal strips were used to join and seal one panel to the next. The hut became known as the Nissen Bow Hut. More than a hundred thousand Nissen Bow Huts were fabricated to support British troops during WW1.[28]

The Nissen hut was considered the leader of hut technology at the time and was so successful that it became the only hut mass-produced by the British government toward the end of the war. The huts are believed to be the first complete, mass-produced buildings.[29] Nissen also created a 20 feet x 60 feet hut known as the Nissen Hospital Hut. Though the design of the Nissen hut was very efficient in terms of constructability and portability, the hut is a poor insulator. The insulating qualities of Nissen's hut depend primarily on the air space remaining between the inner and outer metal sheet. This type of structure may have been an acceptable solution for a war fought in a temperate climate location, but it would not adapt itself well to cold or hot areas.

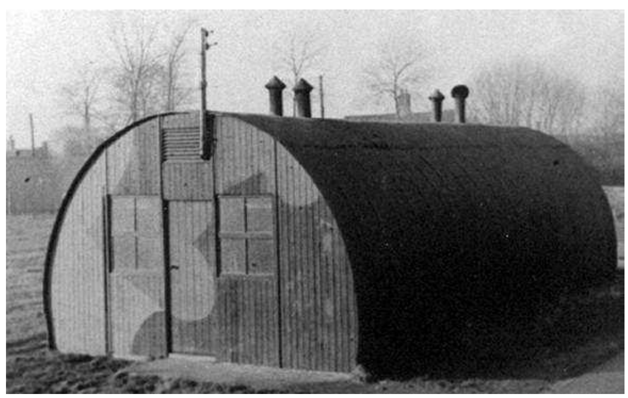

Figure 9: Nissen Hut

5.1.3.2 Quonset Hut:

In 1937 as the United States began to prepare for World War II, the government authorized an increase of about 25 additional air bases, both in the U.S. and overseas.[30] Two organizations- the George A. Fuller and Company and the Merritt-Chapman and Scott Corporation were selected for the construction of one of the bases, known as the Quonset

[27] Chiel, Chris, and Julie Decker.*Quonset Hut: Meal Living For The Modern Age*. 1 ed. New York: Princeton Architectural Press, 2005. pg. 5
[28] Ibid. pg.6
[29] Ibid. pg.6
[30] Ibid. pg. 1

Point. Fuller and Scott were so proficient together as a team that they were asked to construct another base in Argentina before Quonset Point was completed. Then as the Quonset Point was nearly complete, the government asked Fuller and Scott to develop and produce a new prefabricated hut system to shelter troops abroad. Per request, these buildings would need to be designed for mass production, able to be portable, erected and knocked down quickly and easily, adaptable to any climate and geography, and provide soldiers with the most protection and comfort possible.[31]

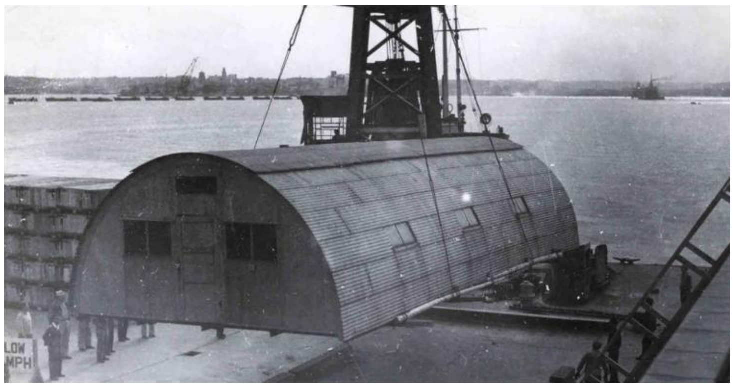

Figure 10: Quonset Hut

Using the British Nissen Hut as the starting point for the design, Fuller and McDonnel came up with a simpler design known as the Quonset Hut (Figure 10). According to Fuller, "The British had been on the right track but too many gadgets slowed erection; and with no insulation between inner and outer metal shells, the Nissen huts were hot in the summer and cold in the winter.[32] Fuller and McDonnell claimed the Quonset hut as almost a complete redesign of the Nissen hut. However, in reality both huts are very similar in terms of the structural system. Both systems were built from the inside out- first laying the interior wall against the inner flange of the T-Rib arch and then working out to the corrugated metal exterior. The major difference between the two huts is the design of the interior. Rather than depending on primary corrugated metals, the Quonset hut uses a thin, lightweight pressed-wood lining of 3/16-inch Masonite held to the rib flange with an attachment clip, and then overlaid with a one-inch thick layer of wading paper insulation.[33] The huts went on fully operational, mass-production on 11 June 1941.

[31] Ibid pg.3
[32] Ibid. pg.6
[33] Ibid. pg. 7

Fuller and McDonnell's design team also went on to create 41 design variations that served as a multitude of needs for the military's forward bases. Each specialized hut design indicated the building modifications necessary to make the conversion and location of equipment necessary for a particular design. In tropical climates, adjustments were made in the form of increased venting, water collection troughs, and overhangs. In cold climates, residual framing lumber was often used to create arctic entries, separated enclosed entrances that trapped the cold air from entering the hut. Some field modifications were also commonly made to the Quonset huts. For instance, depending on the slope of the site, the conditions of soils, the availability of local materials, and urgency of construction, a foundation is sometimes required for the construction.

5.1.3.3 K-Span

K-span buildings are pre-engineered metal structures ideal for use as large facilities because they have a large clear floor area without columns or other obstructions (Figure 11). The design allows floor-to-ceiling storage of material and wall-to-wall placement of machinery. The column-free interior also allows for efficient shop layout. Another advantage of this structure is the ease of construction. When the structure is not in use, it can be disassembled, stored, or moved to another location and re-erected because only bolted connections are used. The frame is strong and designed for working loads of 20 pounds per square foot load, plus the dead load, and the load from a 70 mph wind. The building can also be easily modified to varying lengths and purposes by taking out or adding bays or substituting various foundation and wall sections. The one and biggest problem with the K-span is the extensive work required before the actual erection of the building. After the building site is located, the foundation has to be set and all the materials have to be uncrated and laid out in an orderly manner.

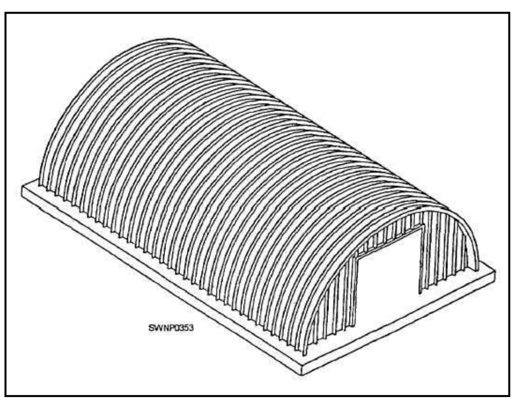

Figure 11: K span

5.1.4 Modular buildings or trailer units

5.1.4.1 ISO Shelters

ISO (International Organization for Standardized) shelters are based on the basic dimensions of a freight container, typically referred to as an ISO Standard 1161. ISO shelters provide a highly mobile, environmentally controlled work/live-in space for applications such as field hospitals, maintenance facilities, tactical operations centers, command post, field kitchens, modular print systems, surgeries, and laboratories. Expandable ISO shelters are available in three distinct models: Non-expandable, one-side expandable, and two-side expandable (Figure 12-L).

Based on an ISO Standard 1161, the containerized housing unit (CHU) is designed as a light construction consisting of floor and roof frames and corner profiles (Figure 12-R). This type of construction allows the compounding of individual containers in longitudinal and transverse directions. It also allows the capability to stack the containers two to three floors in height. The wainscots of the container are made of light insulation panels. Containers can be delivered in kits just 648 mm high.

Figure 12: Expandable ISO Shelters (L) and Containerized Housing Unit (R)

5.1.5 Prefabricated and manufactured buildings

5.1.5.1 Southeast Asia Hut (SEA hut)/Southwest Asia Hut (SWA hut)

Southeast Asia hut (SEA hut) is a semi-permanent construction facility that uses standard dimensional lumber and plywood construction. The SEA hut was originally developed in Vietnam for use in tropical areas by U.S. troops as sleeping quarters (Figure 13). The standard size of a SEA hut is 16 feet wide by 32 feet long. SEA hut provides adequate shelter against weather. They are used as a temporary solution to housing forces for operations that exceed 6 months in duration. However, its conventional construction requires large quantities of Class IV

(Wood) supplies that generate logistical problems. Similar huts were constructed in Kosovo, Bosnia, Kuwait, and Iraq. Due to the different locality, these huts were renamed as Southwest Asia Hut (SWA hut).

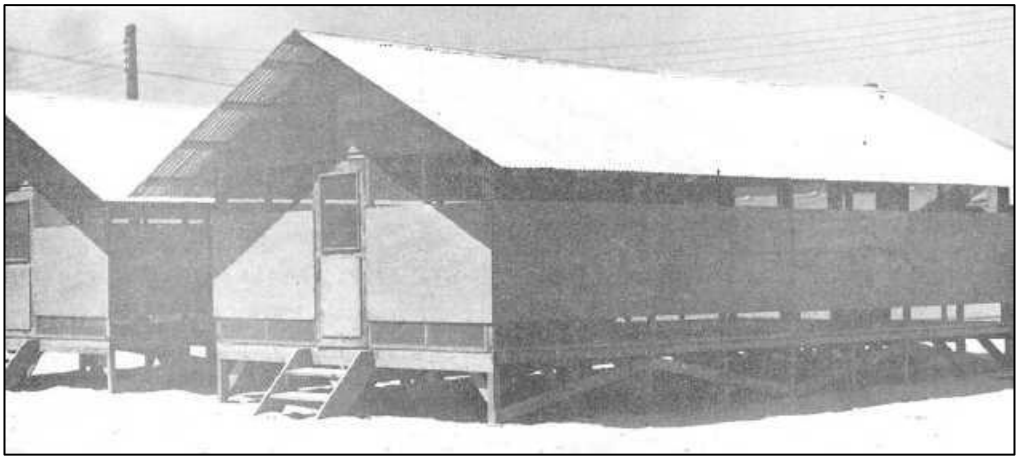

Figure 13: SEA Hut

5.2 War Shelter Assessment

Using pre-existing structures can be the least-time consuming option for providing needed facilities for mission accomplishment, but the original design, intended use, and current structural integrity of the pre-existing structures may not meet mission requirements. In many cases, pre-existing structures are limited depending on the area of operations.

Tents are a quick means of establishing basic life support areas and minor mission support areas if readily available like the pup tent. However, long-term use of tents and their impact on quality of life and level of protection may be inadequate. The longer the tent is used and exposed to environment conditions, the less likely it is to be easily repacked and stored for reuse. Therefore, the planned length of use plays a very important role in determining the suitability of tent usage. Meanwhile, a tent can be converted into different tiers to strengthen its structure and extend its lifecycle.

Pre-engineered metal or fabric buildings are structures that are assembled on-site out of standard components and materials brought to the site. Custom designs for specific sites and usage requirements, and prepackaged and assembled kits ready for construction are available. Pre-engineered metal or fabric buildings are rapidly constructed, mobile, transportable, flexible in design, durable and low maintenance, and minimal in foundation and preparation requirements. However, a disadvantage is that some of the major structural components are quite large and bulky in nature, making mobility and transportability inefficient.

Modular buildings or trailer units are fabricated or assembled off-site, transported to the site, and placed in position. One of the advantages of modular buildings is that they come complete with all the necessary components including walls, floors, windows, heating and cooling, plumbing, electrical wiring, and interior finishes. These structures vary in size and cost, and can be very versatile and flexible. Other advantages of modular buildings include cost savings, speed of occupancy, ease of expansion, and ease of relocation. The most significant advantage of modular buildings is the significant on-site time saved. However, access and appropriate foundation are possible concerns and disadvantages when placing these structures.

Prefabricated and manufactured buildings are created in a controlled factory environment, delivered to prepared building sites, and assembled and installed on-site to complete the unit. Like modular buildings, prefabricated buildings come with all the necessary components. Some significant advantages include self-supporting, ready-made components, quality control, and reduced construction time. Meanwhile, possible leaks from joints in fabricated components and high transportation cost are some disadvantages.

Each type of military structure discussed comes with advantages and disadvantages. Depending on the mission and duration of operation, one structure might be more beneficial than another. Some structures are intended for a short period of use, like tents and tensile fabric, while some are constructed for a more permanent and extended period of use like prefabricated and manufactured buildings. There are also many other elements that factor in the preference of each structure such as materials, cost, durability, modularity, and transportability. Therefore, a thorough assessment of the type of facility needed for the operation is recommended.

6. MILITARY STANDARDS

The military is governed by standards. There are standards established for base camps, housing, construction, and operations. Different types of operations have different sets of procedures. These standards are established not only to ensure that operations are executed properly and efficiently, but also to make certain that a soldier's quality of life is maintained. Therefore, understanding how the military operates is essential to the process of developing a new housing model for it.

There are different military operational bases established for different reasons. There are primarily two types of operational bases: permanent and contingency. Permanent bases are created for enduring missions while contingency bases are formed for immediate and temporary operations, typically overseas. The focus of this project is the development of a new housing model for the purpose of contingency operations. The purpose of this section is to highlight the various military standards that are relevant to this project: military's standards and views on quality of life, standards for contingency operations and constructions. This section of the document also serves as background knowledge for those who are not familiar with military terminologies and standards of operations. More details and standards regarding this type of base follow.

6.1 Army's Standards and Views on Quality of Life

The U.S. Army defines quality of life as "the provision of equitable, adequate, and appropriate living, working, and leisure conditions consistent with available resources and political and military considerations."[34] The Army recognizes that the soldier's quality of life is affected by both working and leisure conditions; facilities and services must be equitably provided; and quality of life provisions are constrained by available resources and political and military considerations. Recent experiences in such places as Bosnia, Kosovo, Kuwait, and Iraq have become test beds for engineering and base camp construction. The quality of life for deployed soldiers has become increasingly important because of the frequency of deployment, and base camp facilities have had to improve the standards initially planned for by military standards.[35]

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[34] Schuster, Carol R., *Quality of Life in the Balkans.* pg. 7

[35] Headquarters, Department of the Army. "FM 3-34." Engineering Operations. www.fas.org/irp/doddir/army/fm3-34-400 (accessed February 13, 2011).

For Army base camps, the Army established the Red Book, which provides standards covering housing; unit facilities; soldier support facilities; and morale, welfare, and recreational facilities. Published in 1997, the Red Book provides minimum standards for the construction of camp facilities. The standards are expressed in terms of square feet, quantity, and construction materials. The handbook is designed to ensure adequate facilities for soldiers and civilians deployed in contingency operations under United States Army Europe (USAREUR) command. Authorized levels of support are derived from Army Regulations and from five years of lessons learned in the field. This handbook's goal is to take the intent of Army Regulations regarding installation and to apply them to contingency operations. While all construction in contingency operations is temporary in nature, guidelines have been added to ensure an extended effective lifespan of temporary facilities when needed. In response to ongoing deployment, the Army has also created the Blue Book to provide standards for services available to deployed personnel. The Blue Book's minimum standards, which are applied by camp commanders, specify accessibility, availability, and quality.

6.2 Standards for Main Base Camps

A base camp is an evolving military facility that supports the military operations of a deployed unit and provides the necessary support and services for sustained operations.[36] Main base camps are those occupied by a battalion task force or larger unit (500 or more). They are continuously operated camps with command, staff, and logistic functions. The standards outlined in this section apply to all main base camps. They are broken down into four areas: housing standards, unit facility standards, personnel support standards, and utility standards. Each facility is further broken down into two states of building types: initial and end state. Refer to Appendix B for details.

6.2.1 Troop Housing Standards

Soldiers and civilians are initially housed in tents until SEA huts or containers are put in place. Table 1 gives the authorized square footage of billeting space for soldiers and officers. Table 2 shows the basic planning guidance for troop housing based on base camp size. Assuming that there is a 20/80 officer to enlisted ratio, 110 square feet of space are required for

[36] Headquarters, Department of the Army. "FM 3-34." Engineering Operations. www.fas.org/irp/doddir/army/fm3-34-400 (accessed February 13, 2011).

per officer and 72 square feet per enlisted. Figure 14 shows how SEA huts are organized into company groupings ("clusters"), with a collocated latrine and shower container.

Category	SF	# per SEA hut	# per Container (8 x 20)
E1-E5, GS-6 & below	80	6	2
E6-E7,WO-1/2, O1-2, GS7-9	90	4	2
E8, CW-3/4, O3-4, GS10-12	100	3	2
CW5, O5/6, GS-13-15, E-9	125	2	1
SES, O7	300	1	1

Table 1: Authorized Living Square Footage[37]

Base Camp Size	*Officer (sq ft)*	*Enlisted (sq ft)*
500	11,000	28,800
1,500	33,000	86,400
3,000	66,000	172,800
10,000	220,000	576,000
Note. Assumes 20/80 officer to enlisted ratio; 110 sq ft per officer; 72 sq ft per enlisted		

Table 2: Basic Planning Guidance for Troop Housing[38]

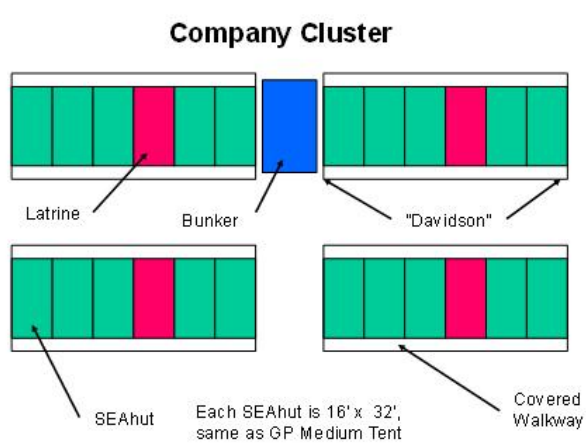

Figure 14: SEA Hut Grouping Diagram[39]

[37] Construction and base camp development in the USCENTCOM area of responsibility (AOR) "The Sand Book". Headquarters United States Central Command. 17 Dec 2007.

[38] Headquarters, Department of the Army. "FM 3-34." Engineering Operations. www.fas.org/irp/doddir/army/fm3-34-400 (accessed February 13, 2011).pg. E-5

A standard SEA hut is 512 square feet, with a standard SEA hut cluster (Davidson) having five bays and a latrine, for a total of 2,944 square feet. SEA hut structures provide a high level of safety and comfort by providing personnel with linoleum flooring, electric heat and cooling (if the climate requires), electric lights, and electrical connections. SEA huts organized in this manner have connecting covered walkways that minimize the distance personnel are required to walk to shower facilities. Finally, housing organized in this manner increases unit cohesion by maintaining company, platoon, and squad integrity.

6.2.2 Quality of Life Standards for Tents

Tents are meant to establish quick basic life support facilities during the early stage of the operations. However, the tents can be converted to different tier levels for transition to a more enduring temporary and semi-permanent facility. There are three tier levels for tent constructions (Table 3). Size and usage also varies from tent to tent. Table 4 illustrates the planning factor for tentage constructions.

Tier Level	***Bed-Down and Base Camp Living Standards***
Tier I	Simple tent setup without floor, nonpermanent
Tier II	Wooden floor, lights, pole-supported, 2 electrical outlets
Tier III	Slightly nicer wooded floor, 2/3 wooden wall structure with frame, more electrical outlets

Table 3: Quality of Life Standards for tentage[40]

Type	***Floor Area (sq ft)***	***Weight Packed (lb)***	***Volume Packed (cu ft)***
Tent, GP, small	198.9	163	26.2
Tent, GP, medium	512.0	534	33.0
Tent, GP, large	936.0	665	69.0
Tent, ext modular (temper)	640.0	2,192	200.0
Tent, maintenance, medium	640.0	1,798	62.0
Note. Operation Joint Endeavor living standard was 10 soldiers per GP medium.			

Table 4: Selected tentage planning factors[41]

[39] Construction and base camp development in the USCENTCOM area of responsibility (AOR) "The Sand Book". Headquarters United States Central Command. 17 Dec 2007.
[40] Headquarters, Department of the Army. "FM 3-34." Engineering Operations. www.fas.org/irp/doddir/army/fm3-34-400 (accessed February 13, 2011).pg. E-5
[41] Ibid.pg. E-5

6.3 Contingency Operations

According to the Sand Book published in 2004, basing falls into one of two categories: permanent or contingency. Permanent base is associated with long-term strategic force stationing while contingency base is associated with short-term immediate operations. Focusing on specific site conditions rather than on a specific locality, this project's intended use is for contingency bases. Contingency operations are temporary in nature. Currently, there are three types of contingency bases: Contingency Operation Bases (COB), Contingency Operation Sites (COS), and Contingency Operation Locations (COL). A contingency base is usually occupied by an element larger than Unit of Action (UA) size from a single service or joint services. Its purpose is typically a command and control hub and/or regional logistics hub, characterized by advanced infrastructure for facilities and communications for the expected duration of the operation or exercise. A contingency site is usually occupied by a UA-size element or smaller capable of providing local and regional operations, security, and/or humanitarian assistance relief. The site size and capabilities are scalable to support rotation of forces or prolonged contingency operations. Characterized by limited infrastructure, a COS may be dependent on some contracted services. A contingency location is usually occupied by a battalion-size element capable of quick response to operations, security, civic assistance, or humanitarian assistance relief. A COL will be dependent upon a COS or COB for logistical support and characterized by stark infrastructure primarily dependent on contracted services or field facilities. A COL consolidates to a COS as the contingency matures.

Contingency base camp support construction is characterized as either being initial or temporary. Initial standards include expeditionary up to initial camp standards. Expeditionary facilities are designed and constructed on an expedient basis, using unit organic and service provided equipment and systems, and/or host nation resources to support the mission. They provide support, facilities, and the infrastructure necessary to receive, bed-down, and support operations of deploying forces. Initial facilities are designed and constructed on an expedient basis and characterized as austere and requiring minimal engineering effort. The initial standard is intended for immediate operational use by units upon arrival for a limited time. These initial and temporary facilities may require replacement by more substantial and durable facilities during the course of operations.

Contingency-based planning is a planning strategy that deals with uncertainty by identifying specific responses to possible future conditions.[42] A contingency-based plan typically consists of various if-then statements that define the solutions to be deployed if certain problems occur. Recognizing that the future is impossible to predict and that conditions may change, contingency-based planning offers a variety of flexible and responsive solutions. Contingency-based planning tends to reduce costs, improve efficiency, and expand the range of possible solutions compared with more rigid planning. Contingency-based planning generally involves the following steps:

1. Identify objectives and targets
2. Identify various solutions
3. Evaluate the costs and benefits of each strategy
4. Implement strategies
5. Evaluate the program and strategies based on various performance measures to insure effectiveness

Considering the frequency and possibility of U.S. military soldiers being deployed to various parts of the world in the future and given that one fifth of Earth's land mass is covered by deserts, this project will focus on the design of a war shelter module for hot, dry, and cold environmental conditions.

6.3.1 Contingency Base Camp Standards

According to the Red Book published by the military, contingency base camp standards are intended to be used only as a guide in advance of or in the absence of direction from higher headquarters. Contingency construction standards apply to locations where no camp infrastructure exists; where existing support infrastructure does not meet surge requirements levied by the mission; and where an interim measure in support of building permanent infrastructure to support Main Operating Bases (MOB), Forward Operating Sites (FOS), and Cooperative Security Locations (CLS) is required.[43] Refer to Appendix C for outline standards per facility and type of construction.

[42] Administration, the US Federal Highway, and describes analytical methods for. "Online TDM Encyclopedia - Contingency-Based Planning." Victoria Transport Institute - Main Page. http://www.vtpi.org/tdm/tdm123.htm (accessed March 7, 2010).

[43] Construction and base camp development in the USCENTCOM area of responsibility (AOR) "The Sand Book". Headquarters United States Central Command. 17 Dec 2007.

6.4 Military Standards of Construction

Peacetime contingency operations are time sensitive. Construction standards are intended to minimize the engineer effort expended on any given facility while assuring that the facilities promote sufficient quality for personnel health and safety and mission accomplishment. The intended life span of the facilities and infrastructure of a base camp depend upon the duration of the operation. There are two phases of construction standards, based on anticipated lifespan of the base. The two phases are the contingency phase, which spans from 0-2 years and the enduring phase, which is defined as 2 or more years. Within each of the phases are subset standards which further define the phases. There are three subsets of construction standards for contingency operations. During the life cycle of each phase, the facilities may progress from initial to semi-permanent, or may be immediately established at any level depending on the requirements of the operation. These structures will progressively improve to meet the living standards as the operation extends. Figure 15 illustrates the development of a base camp.

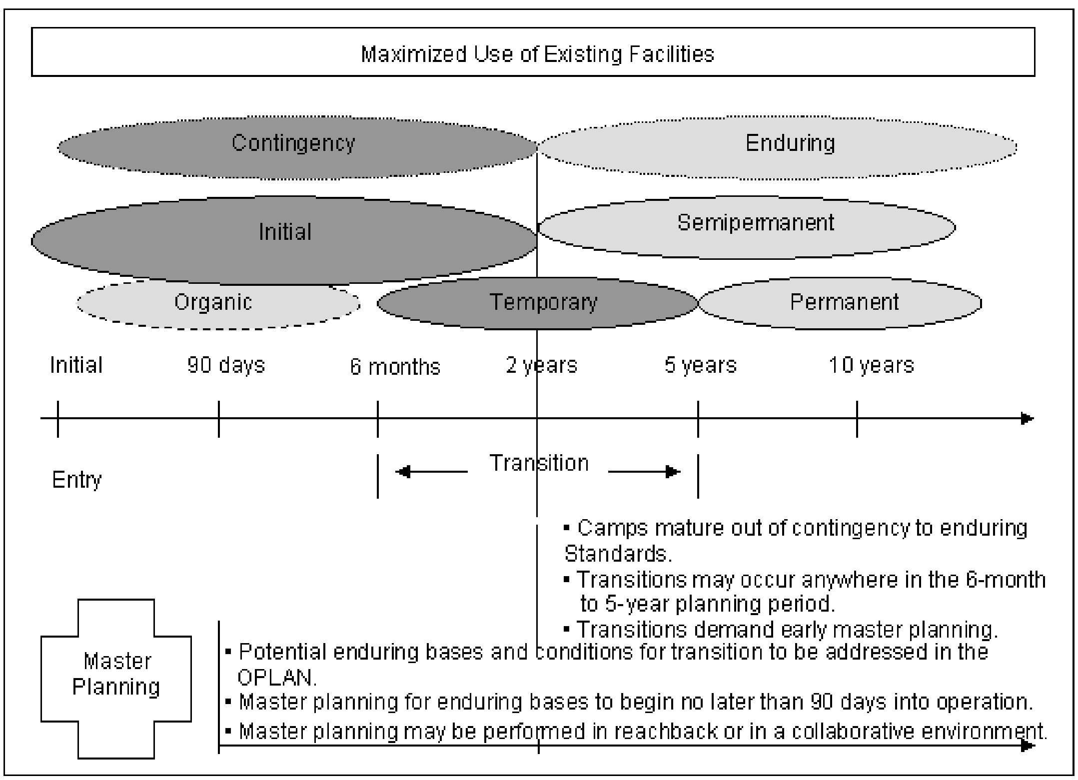

Figure 15: Base Camp Development

6.4.1 Contingency Phase Standards Defined By Phase

Organic construction standards are set up on an expedient basis with no external engineer support, using organic equipment and resources. Organic in this case is referred to the fundamentals, using the basis resources and personnel available. This type of construction is intended for use up to ninety days or six months, and is typically used for initial force presence and maneuvering activities until force flow supports the arrival of engineer resources.

Initial construction standards are characterized by facilities requiring minimal engineering effort and the ease of material transportability or availability. It is intended for immediate use by units upon arrival in theater for up to six months. As operations endure, a replacement by more substantial or durable structures may be required.

Temporary construction standards are characterized by facilities requiring additional engineer effort above that required for initial standard facilities. Temporary standards are intended to increase efficiency of operations for use up to twenty-four months, but may fulfill enduring phase standards up to five years.

6.4.2 Enduring Phase Standards Defined By Phase

Semi-permanent construction standards are characterized by facilities that are designed and constructed with finishes, materials, and systems selected for moderate efficiency, maintenance, and lifecycle cost and with a life expectancy of more than two years.

Permanent construction standards are designed and constructed with finishes, materials, and systems selected for high-energy efficiency, low maintenance, and lifecycle cost. This type of structure has a life expectancy of more than ten years.

6.5 Design Considerations

Key considerations for the application of general engineering in an area of operation include speed, economy, flexibility, decentralization of authority, and establishment of priorities. Given that time, materials, manpower, and equipment are limited in a deployable environment, speed is critical. Efficient use of personnel, equipment, and materials is also critical. Due to the rapidly changing situation during operations, structures must be adaptable and flexible to all conditions. The standard plan must allow for adjustment, expansion, and contraction whenever possible.

Field Manual (FM) 3-34-400 is designed primarily to assist Army engineers at all echelons in planning and coordinating general engineering operations at the strategic, operational, and tactical levels.

6.5.1 Base Camp Construction Estimating

Base camp construction cost varies according to the size and type of structures, the amount engineering effort required, key materials, and base camp size. Below are two tables from FM 3-34-400 that are designed to be used during initial planning for base camp construction (Tables 5-6).

Base Camp Size	Short Tons	Equipment Hours	Man-Hours			
			Horizontal	Vertical	General	Total
500	2,755	77	3,506	33,175	10,232	46,913
1,500	7,698	247	8,124	86,047	26,331	120,502
3,000	15,138	503	15,093	171,012	53,730	240,070
10,000	50,460	1,680	51,093	570,040	179,100	800,233

Table 5: Summary Table, base camp engineer construction effort

Base Camp Size	Real Estate Acre	Fine Aggregate (cu yd)	Course Aggregate (cu yd)	Potable Water (GPD)	Sewage (GPD)	Electricity (kW)
500	16.0	450	620	12,500	8,750	182
1,500	51.4	1,700	2,485	37,500	26,250	486
3,000	104.7	3,320	4,820	75,000	52,500	988
10,000	350	11,200	16,066	250,000	175,000	3,293

Table 6: Summary Table, base camp aggregate, and utilities requirement

6.6 Base Camp Case Studies

6.6.1 South Vietnam

Originally, there were no set construction standards except limitations on living space and the general admonition that facilities would be minimum and austere.[44] Construction standards evolved slowly and were inconsistent. Theater standards were finally developed and accepted to minimize costs based on duration of occupancy and construction time. The factors that played a major role in determining standards were the mission of the unit for which

[44] "Chapter IV: Planning and the Construction Concept." US Army Center Of Military History. http://www.history.army.mil/books/Vietnam/basedev/chapter4.htm (accessed February 7, 2010).pg.43

facilities were provided, the permanency of units in a given location, and the philosophy of each military service. For instance, both Army and Marine Corps ground combat units have traditionally been equipped and trained to operate in the field with minimum facilities.[45] The rise in temporary troop accommodation standards came into being because combat operations were conducted and supported from relatively static base camps and logistical facilities.

As the war continued, other planning issues not envisioned in the initial planning arose, such as the need to increase cold storage facilities due to large-scale use of frozen foods. The permanency of the base and the life expectancy of a facility or complex were also important factors. The tropical climate justified use of air conditioning for administrative and planning areas. The first general guidelines for construction standards for Southeast Asia cantonments were published on June 4, 1964 (Table 7). After a revision in October 1966, the standards were simplified into three cantonment standards based on expected tenure of occupancy: temporary, intermediate, and field.

Temporary (Category A):

Cantonments for forces not expected to move in the foreseeable future. Occupancy for over 48 months.

Intermediate (Category B):

Cantonments for forces subject to move at infrequent intervals. Anticipated duration of occupancy: 24-48 months. Wood or concrete floors with tent frames, roofs, some paved roads, full electrical utilities, and minimum requirements for latrine facilities.

Field (Category C):

Cantonments for forces whose activities are such that they may be characterized as essentially transient. Occupancy of less than two years. Wood floors, tents, dirt roads, minimum essential requirement latrine facilities, and minimum utilities.

[45] Ibid.pg.44

Facility	Temporary	Intermediate	Field
Troop housing	Austere wood buildings; 1- and 2-story barracks	Austere wood huts; tents with wood frame and floors	Austere wood huts; Class IV tents with wood frames and floors
Mess hall	Pre-engineered metal or wood building	Pre-engineered metal or wood building	Wood building; tents
Dispensary	Pre-engineered metal or wood building	Pre-engineered metal or wood building	Wood building; tents
Electricity	Central power and distribution	Nontactical generators	Nontactical generators; TOE generators
Water supply	Piped water distribution	Point supply with limited distribution	Point supply
Sewage	Waterborne	Consolidated treatment	Burn-out latrines burn-out latrines
Roads	Paved	Stabilized	Dirt

Table 7: First general guidelines for construction standards for Southeast Asia Cantonments

6.6.2 Iraq

At the start of the war in Iraq, the U.S. had no intention of establishing a permanent military presence there. However, as the operation to support and provide combat assistance in Iraq continued, the U.S. government decided to consolidate the American troops in Iraq into four large air bases: Tallil in the south, Al Asad in the west, Balad in the center, and either Irbil or Qayyarah in the north. Initially referred to as “enduring bases” meant to serve troops in Iraq for at least two years, these four bases were redesignated as “Contingency Operation Bases” (COBs) responsible for providing continued logistical support and emergency combat assistance for the Iraqi Forces if necessary. These are also a part of the withdrawal expected to occur in phases as the U.S. gradually turns over the established bases to the Iraqi forces. Each COB will support a brigade combat team along with aviation and other support personnel. Long-term facilities, such as concrete barracks and offices, are planned for these bases.

Currently, there are two main types of structures erected throughout Iraq: expeditionary and temporary structures. Expeditionary structures are structures intended to be inhabited for no more than one year after they are erected. This group of structures typically includes tents, small and medium shelter systems, expandable shelter containers, ISO and CONEX (Container Express) containers, and General Purpose (GP) medium tents, and GP large tents. Temporary structures are structures that are erected with an expected occupancy of three years or less. This group of structures typically includes wood frame and rigid wall construction, such as Southeast Asia huts, hardback tents, ISO and CONEX containers, pre-engineered buildings, trailers, stress tensioned shelters, Expandable Shelter Containers (ESC), and Aircraft Hangers (ACH).

6.7 Military Standards Assessment

Understanding the standards of military base camp development and construction is critical to the feasibility and comprehensiveness of this doctorate project. Due to the frequency of deployments in Iraq and Afghanistan, the quality of life for mobilized soldiers has become increasingly important. One of the many areas that affect a soldier's quality of life is housing. Housing standards are governed by the phase of construction. Based on the current model and the two case studies explored, there are typically three phases of construction in a contingency environment: organic, initial, and temporary. Each phase of construction is characterized by different type of structures. These military standards provide a set of basic guidelines and planning principles for the new war shelter design model.

7. SURVEY & EVALUATION

Gathering data from a survey can help to further support a research. In some cases, a survey can make changes come into reality. In 2001, the office of the Assistant Chief of Staff for Installation Management (OACSIM) and Headquarters of U.S. Army Corps of Engineers (HQUSACE) conducted a comprehensive survey to determine the specific changes for permanent barrack construction. Based on the survey, four changes were made to the barracks construction criteria: 1. Established the two-bedroom/one bath module as the standard module; 2. Require installation of a stove or cook top; 3. Require laundries in the barracks; and 4. Eliminate the separate soldier community building.

I know, from personal experience, that living conditions are rough in the desert; however, that is only my own opinion. Therefore, I set out to gather primary data by conducting a survey with deployed soldiers, to assess the quality of life and determine if there are opportunities to improve the quality of life for U.S. forces deployed overseas. The survey outlines questions regarding to the various factors that affect the quality of life while deployed and the housing conditions. Refer to appendix D for details of the survey. Figure 16 is a graph that represents the results from the survey.

Based on a survey of 50 people, the 3 most important factors that affect the quality of life for soldiers deployed to the Middle East are housing, ability to communicate with family/friends, and shower. The least factor affecting the quality of life for deployed soldiers is laundry service. The 3 facilities that soldiers would like the base to improve are gym, recreation, and Post Exchange (PX). The one thing that soldiers would like to improve in the room is privacy followed by internet connections. Almost everyone surveyed was either sort of satisfied or satisfied with their living quarters. However, sand getting inside the quarters seems to be a problem for many during sandstorms. Bugs, insects, and rodents were able to get into some soldiers' room.

Though the majority of soldiers were sort of satisfied with their living quarters while deployed, housing is still considered to be one of the top factors affecting the quality of life for deployed soldiers. In terms of improvement, soldiers insist on more privacy and space inside their room. Finally, the most interesting part of the data collected is that the shower is one of the three important factors affecting the quality of life of U.S. Soldiers deployed to the Middle East.

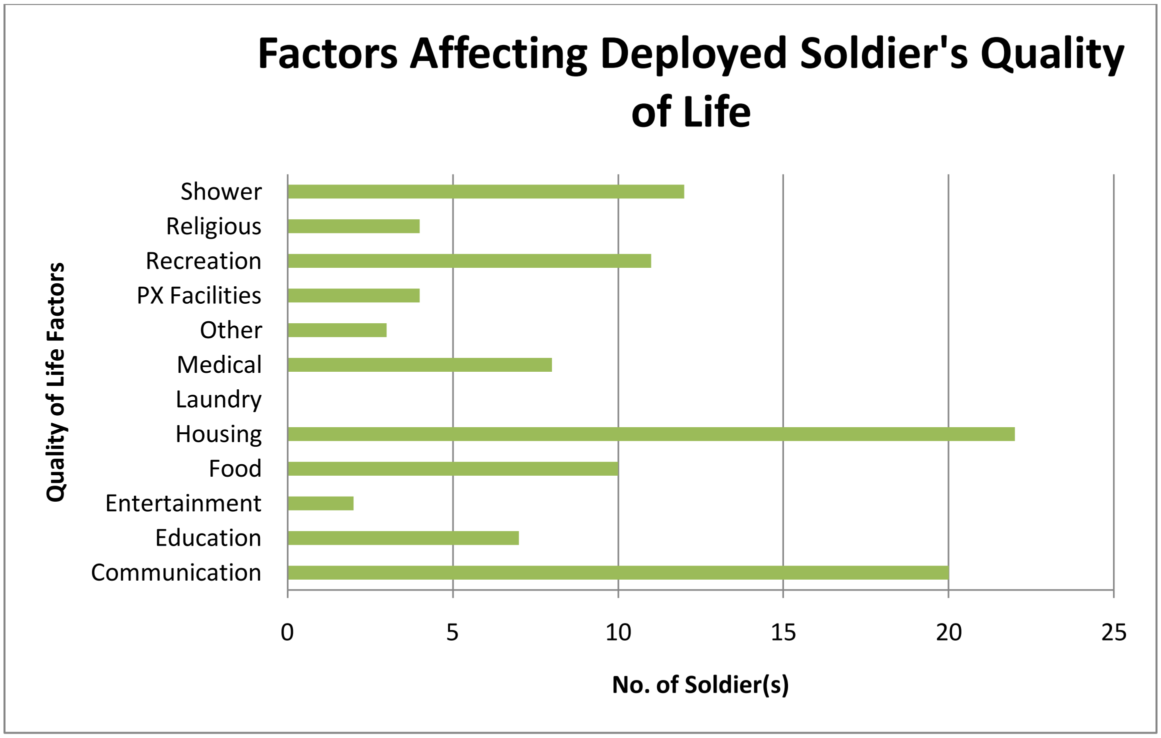

Figure 16: Survey results on the Factors Affecting Deployed Soldier's Quality of Life (Survey Completed in February 25, 2010)

8. BIOMIMICRY

8.1 Biological Analogy in Architecture

Why use biological ideas in architecture? Biological analogy has been reflected in architectural design by intent or accident. *The Evolution of Designs* tells the history of the many biological analogies that have been made between the evolution of organisms and human designs, especially in architecture. Since the beginnings of science studies in the early nineteenth century, architects and designers looked to biology for inspirations. Architecture and designs look not just to understand and imitate the forms of plants and animals, but to grasp a deeper understanding of the biological processes and evolution in nature to derive new models ad methods in design.[46]

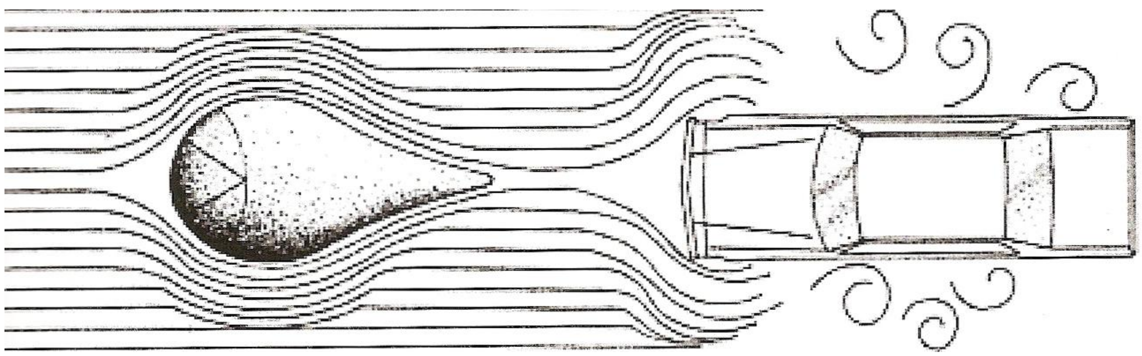

Figure 17: First Car Design Inspired by a Raindrop

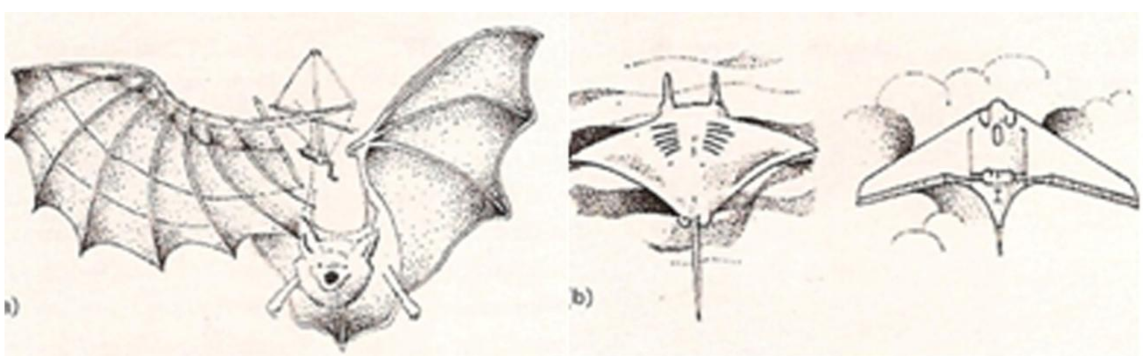

Figure 18: Flying Machines Inspired by a Bat

One of the first car designs was based on a natural shape (Figure 17). In 1933, by studying the shape of the raindrop, Buckminster Fuller designed the Dymaxion automobile based on the same principles. As a drop of rain falls through the atmosphere, its spherical shape is modified as the velocity increases. The front part of the car was modified for the same

[46] Steadman, Philip. *The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts*. New York: Routledge, 2008.

reason. The first flying machines were also inspired by the flight of butterflies and bats (Figure 18). The first flying machine known as Ader's device was developed by studying a bat's membranous, impermeable skin covers and carefully measuring its skeleton structure.

The central concept in the beauty of art is the idea that all parts contribute to the effect or purpose of the whole and no part may be removed without some damage to the whole. Beauty is therefore equal to its fitness for use. Analogy in biology is a constant and recurring theme throughout the history of architecture and often reflected in famous work from architects like Wright, Sullivan and Le Corbusier. Meanwhile, Hersey also points out that there was a problem with biological analogy in architecture in the past because much of the correlation has been based on 'artistic' photos of the wonders of nature through a microscope rather than on in-depth studies of how plants or organisms function.[47]

Biology has also often been reflected in famous work from architects like Wright, Sullivan, and Le Corbusier. Many architectural ornaments are borrowed from plants and animals. Spiral capitals, spiral staircases, spiral columns, and spiral towers are examples inspired by the study of DNA and similar spiral and radial symmetries found in nature.[48] Animals and buildings also share characteristics such as the trait of bilateral symmetry. Buildings, for instance, are organized in a bilateral symmetrical layout similar to that of many animal structures and forms. However, Hersey also points out that there's a problem with biological analogy in architecture of the past because much of the correlation has been based on 'artistic' photos of the wonders of nature through a microscope rather than on in-depth studies of how plants or organisms function.[49] Today, some buildings designs apply biological ideas in the form of symbolic purpose like Calatrava's Milwaukee Art Museum, a building that features a combination of organic forms and technological innovation. Many architectural elements are borrowed from plant and animal forms, patterns, and structures while others emulate biological processes.

8.1.1 Animal Architecture

The reason human beings build structures is not any different from the common function of many animal-built structures, that is, to create a protected home. Likewise, animals build structures to protect against extremes of temperature and the threat of predation.

[47] Ibid
[48] Hersey, George. *The Monumental Impulse: Architecture's Biological Roots*. London: The Mit Press, 2001.
[49] Ibid

Animals also face similar architectural challenges such as ventilation systems, structural complexity, and space planning. Thanks to the ingenuity of man and the advancement of technology, human beings manage to overcome these challenges. However, animals in the wild were able to conquer these issues with minimal help from machines and little or no impact on our planet. So what can we learn from animal-built structures?

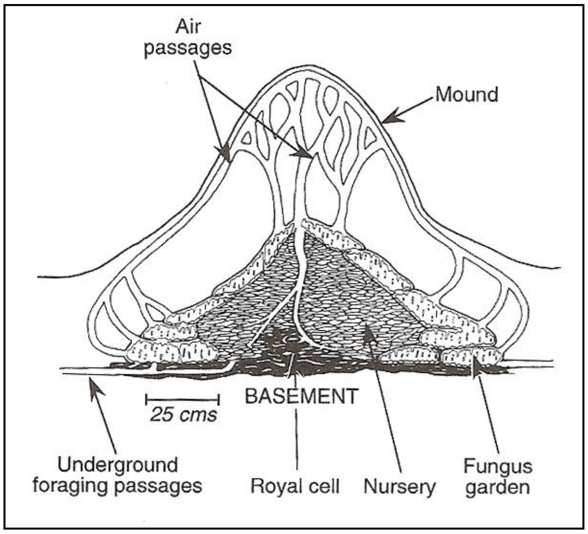

Figure 19: Passive Strategy of Termite Mount

One common adaptive response against temperature extremes and predation risks is burrowing. Burrow architecture alone has allowed a wide variety of organisms to make use of the energy in the fluid medium passing over the burrow exits to power a ventilation system. Burrows of the blacked-tailed prairie dog for instance have exits of two different kinds, lower rounded mounds and steep walled, taller craters. When the wind flows over them, regardless of its direction, air is drawn in through mound apertures and out through the craters. Studies of ant and termite mounds are also great examples of open ventilation design. Air enters at the mound base through the soil or many small foraging apertures and leaves at the center of the dome and side apertures. Macrotermes michaelseni mounds represent a completely different ventilation system. These are enclosed systems of channels where air movement results from temperature differences within the mound. A system of passages originates within the hive area at the base of the mound, then travels up under the outer wall of the mound linking with one or more rising up the mound core (Figure 19).[50] Luscher (1955) uses the mounds of Macrotermes natalensis as a model to explain how closed termite ventilation systems work. He

[50] Hansell, Mike. *Animal Architecture (Oxford Animal Biology)*. New York: Oxford University Press, USA, 2005.

proposes that the heat at the core of the mound generated by termites and their associated fungus gardens rise up through the colony into an open space in the top of the mound. From there, the heat is forced into narrow channels carrying the air near to the mound surface to allow gas exchange by diffusion, and down into a basement below the hive before it is drawn back into the living space above.[51]

8.2 Biomimicry Case Studies

Biomimicry, designs inspired by nature, can be categorized into two general groups: system and form. Below is a list of biomimry case studies selected to represent each group, followed by a detailed description of each design inspiration.

8.2.1 System

8.2.1.1 Velcro

The most famous example of biomimicry was the invention of Velcro brand fasteners by Swiss engineer George de Mestral in 1941. Inspired by the burdock burrs that stuck tenaciously to his clothes and his dog's hair, he developed a two-part Velcro fastener system that uses strips or patches of a hooked material opposite strips or patches of a loose looped weave of nylon that holds the hooks (Figure 20). Today, Velcro is a registered trademark, and the Velcro brand name has become a common term. From shoelaces to special made Velcro used by NASA for fastening astronaut suits and anchoring equipment, Velcro is a daily used product in various forms, sizes, and applications.

Figure 20: Velcro Inspiration

[51] Ibid.pg 7

8.2.1.2 Gecko Tape

Inspired by the gecko’s ability to climb vertical surfaces and walk upside down, researchers from various institutions are working on inventing a tape covered with nanoscopic hairs that mimic those found on the feet of gecko lizards (Figure 21). Millions of tiny, flexible hairs found under gecko feet provide a powerful adhesive effect that can possibly apply to underwater and space stations uses. Gecko tape is an adhesive which uses weak intermolecular attractive forces to be super sticky at one moment and not the next.

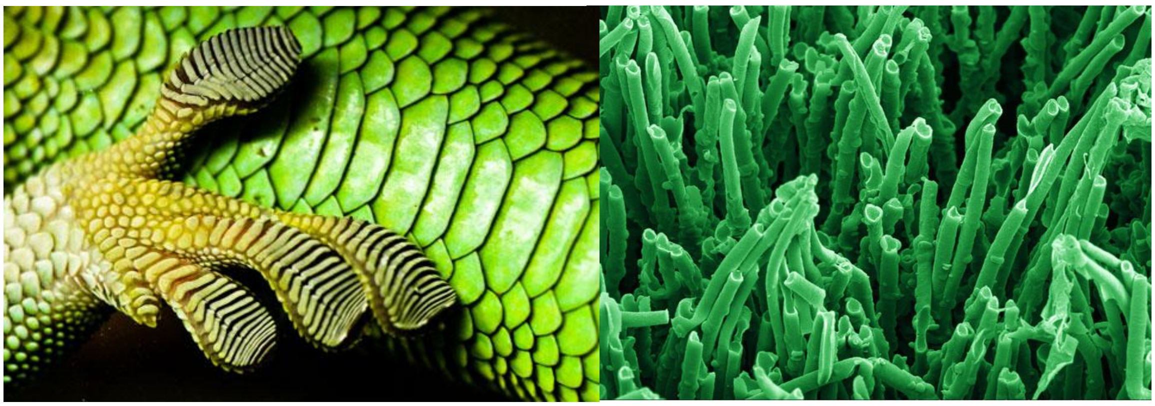

Figure 21: Gecko Inspiration

8.2.1.3 Lotus Effect Hydrophobia

Superhydrophobicity, also known as the “lotus effect” is the process in which water picks up contaminants as it rolls off the surface of lotus leaves due to their bumpy surfaces. Under a microscope, millions of tiny, nail-like protuberances help to repel dust and dirt particles (Figure 22). Inspired by this process, researchers have developed ways to chemically treat the surface of plastics and metal to evoke the same effect. From windshield wipers to paints, the applications of this process are endless.

Figure 22: Lotus Inspiration

8.2.1.4 Eastgate Center (Harare, Zimbabwe, Africa)

Serving as the largest office and shopping complex in Harare, Zimbabwe, the Eastgate center is the most well known example of how biomimicry principles are used to enhance air movement in a building. Designed by Mick Pearce in conjunction with engineers at Arup Associates, the building has no conventional air-conditioning or heating. The building environment is regulated year round with dramatically little energy consumption using design methods inspired by indigenous Zimbawean masonry and the self –cooling mounds of African termites (Figure 23).

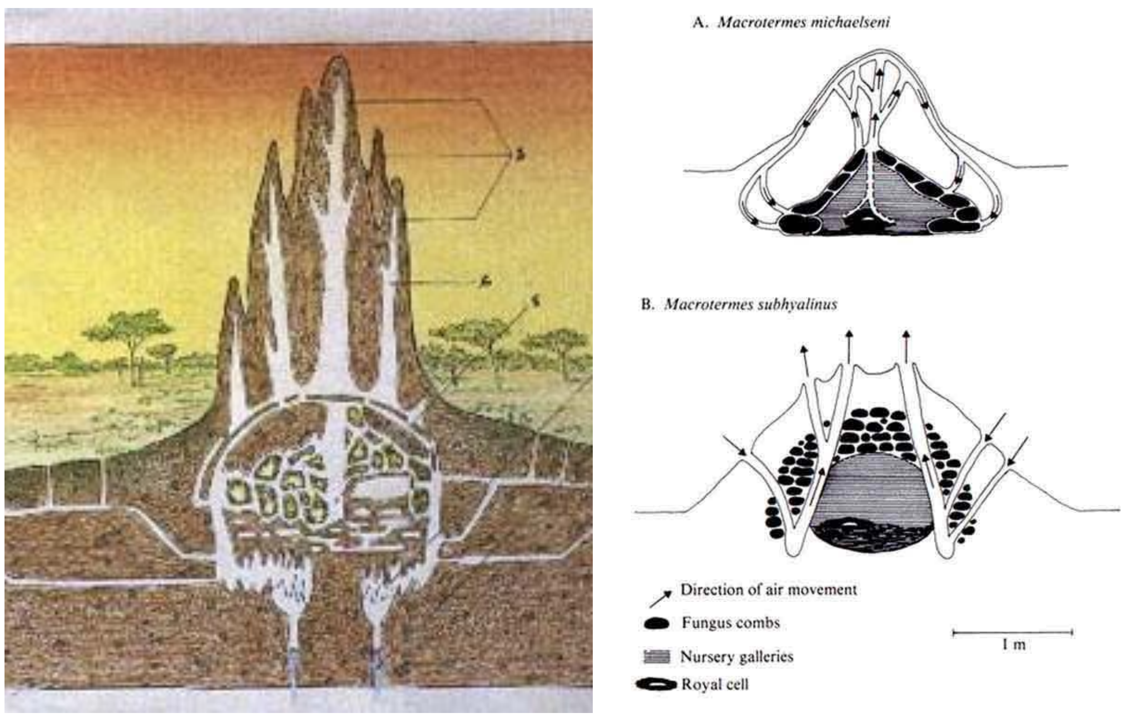

Figure 23: Termite Inspiration

8.2.2 Form

8.2.2.1 Bird Nest Stadium (Beijing, China)

The National Olympic Stadium also known as the “Bird’s Nest” in Beijing, China was built for the 2008 Olympics. Designed by Swish architects, Herzog and Demeuron, it is composed of a grid-like formation that serves as both structure and façade, integrating the stairs and roof onto one cohesive system. The most unique feature of the structure is its cushion system, inspired by a bird’s process of stuffing spaces between woven twigs of their nests (Figure 24). Made from ethylene tetrafluoroethylene (ETFE), the structure of the stadium is filled with inflated cushions that fill gaps to weather- and waterproof the stadium. ETFE is a type of plastic that is designed to have high corrosion resistance and strength over a wide range of temperature.

Figure 24: Bird Nest Inspiration

8.2.2.2 Shinkansen bullet train

Japan's Shinkansen bullet train is the fastest in the world, traveling at over 200 miles per hour. Traveling at such a high speed creates one big problem and that is noise. Every time the train came out of a tunnel, it would produce an extremely loud bang because of the change in air pressure. To solve this problem, the train engineers found a solution in the kingfisher. Inspired by the kingfisher's ability to dive from air to water with little splashing, train engineers redesigned the front end of the train by using the beak of the kingfisher as a model and were able to create a much quieter train (Figure 25). The redesign also helped the train to go even faster and be more energy efficient.

Figure 25: Kingfisher Inspiration

8.2.2.3 Whale Power

Whale power is a new design for a wind turbine which takes its inspiration from whale fins. Through the aerodynamic study of the ribs on a whale's flipper known as tubercles, researchers found that they can significantly prevent stall, a combination of drag and lost lift, which significantly reduces losses in altitude (Figure 26). Inspired by the whale flipper's form, a company was able to create more efficient wind turbines that have doubled the product's performance at speeds of 17 miles per hour.

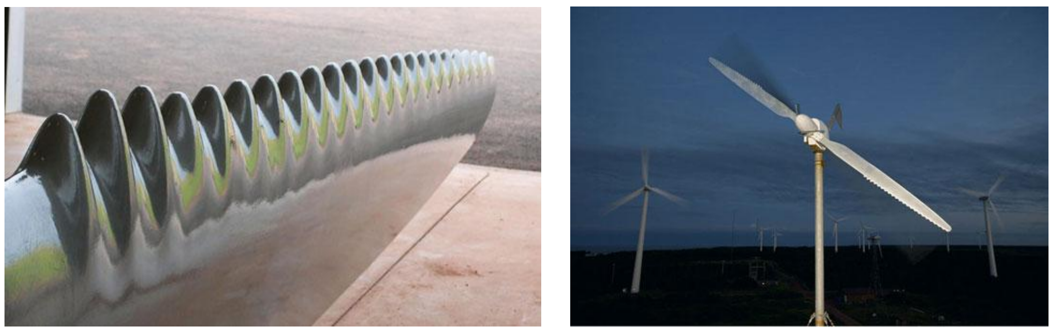

Figure 26: Whale Inspiration

8.2.2.4 Urban Forest Skyscraper (Chongqing, China)

Inspired by mountainous Chinese landscapes and the traditional villages built on the hillsides, MAD architects plans to create a towering vertical Urban Forest. Designed to bring more nature and open space in a dense and compact way, the skyscraper is set in the heart of Chongqing city. Imitating an urban form of a mountain, Urban Forest Skyscraper is a commercial high-rise building with over 70 floors, each one different and unique (Figure 27). Each floor is an abstract curved shape, layered slightly off-center to give the facade an organic look as it rises up into the sky. A central cylindrical core structure supports all the floors and houses the mechanical systems and elevators.

Figure 27: Landscape Inspiration

8.2.2.5 ACME United Nations Memorial Space (Chungju, South Korea)

Inspired by cells, London-based firm ACME designed a memorial space in the United Nations Peace Park in Chungju, South Korea based on individual cells combined together to form a cube structure. The structure is built from hexagonal cells on the exterior and interior parts of the building (Figure 28). The cellular design serves as a multifunction meeting space and houses offices, restaurants, meeting and educational spaces as well as public viewing platforms.

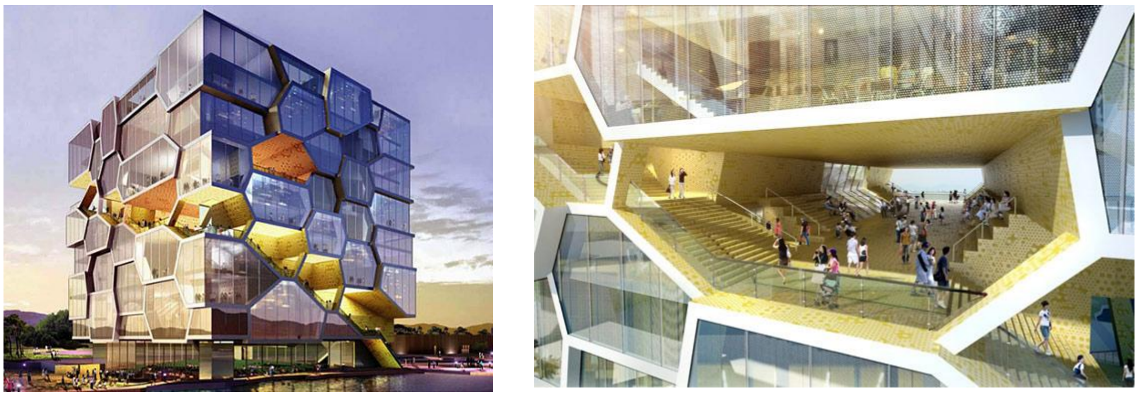

Figure 28: Cell Inspiration

8.2.2.6 Towering Cactus Skyscraper

The Minister of Municipal Affairs & Agriculture in Qatar is designing a brand new office building that takes the form of a cactus. Designed by Bangkok based firm Aesthetics Architects, the modern office and adjoining botanical dome takes cues from cacti and the way that they successfully survive in hot and dry environments (Figure 29). The building is designed to be very energy efficient and utilizes sun shades on its windows. Depending on the intensity of the sun during the day, the sun shades can open or close to keep out the heat when it is too hot. This is similar to how a cactus chooses to perform transpiration at night rather than during the day in order to retain water.

Figure 29: Cactus Inspiration

8.2.2.7 Cocoon Tents

A variety of camping tent designs were inspired by the study of cocoon structures and mechanisms (Figure 30). Similar in function, the tent is used to protect campers from the outdoor environment. Cocoon structures and mechanisms were studied as a natural strategy to achieving the functional needs of a tent such as ease of assembly and the ability to shed water.

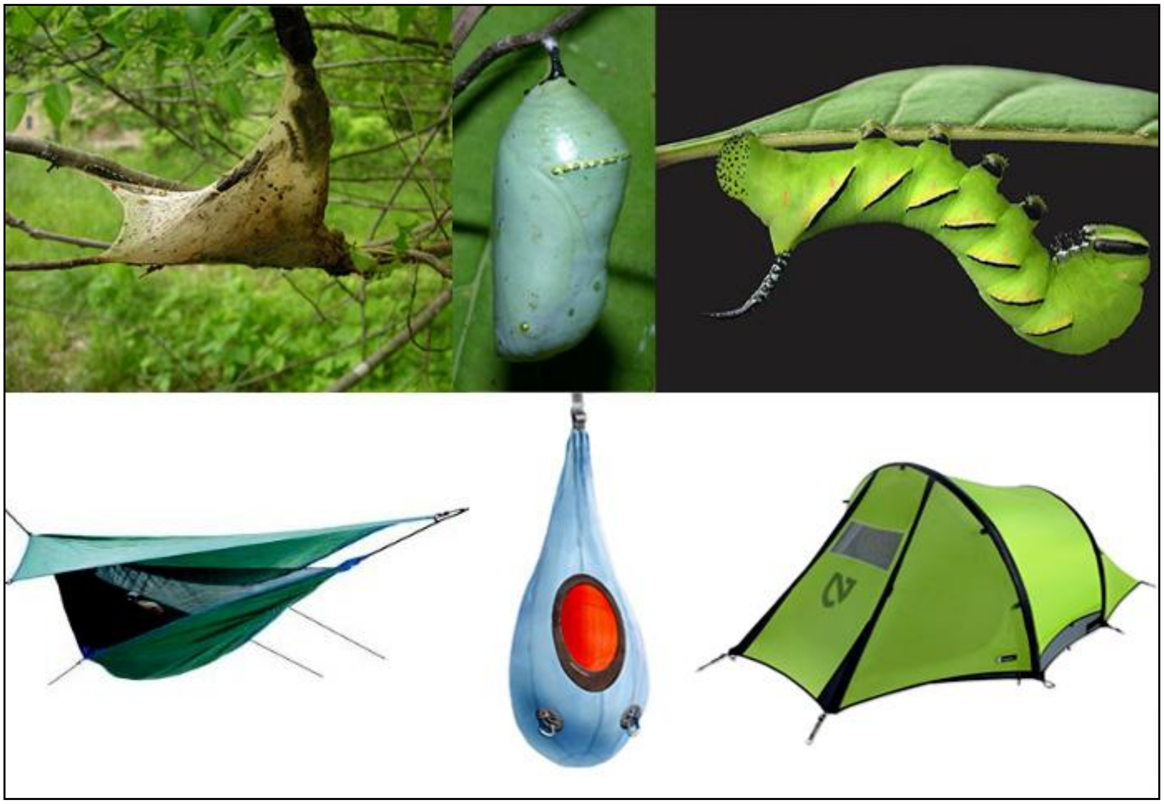

Figure 30: Cocoon Inspiration

8.3 Biomimicry Assessment

From the development of a common adhesive application to the establishment of an efficient high rise tower in Zimbabwe, these all are excellent examples of how nature inspires design and helps to improve the way we live. Understanding how nature sustains itself allows human beings to be more environmentally friendly and less destructive to the planet. Therefore, imitating nature's time-tested patterns is an ideal methodology for eco-friendly design.

9. DESERT ENVIRONMENT

9.1 Desert Biome

About one fifth of the Earth's land mass is characterized by arid to semi arid environment (Figure 31).[52] Arid regions receive less than 10 inches of precipitation a year. Semi-arid regions receive 10-20 inches of precipitation a year. One of the most important factors contributing to aridity is the rate of evaporation. The faster the rate at which water in the form of liquid transform to a gas and vaporize in the air, the hotter the climate becomes. Despite the severe climate of these regions, there are many plants and animals that dwell in this environment.

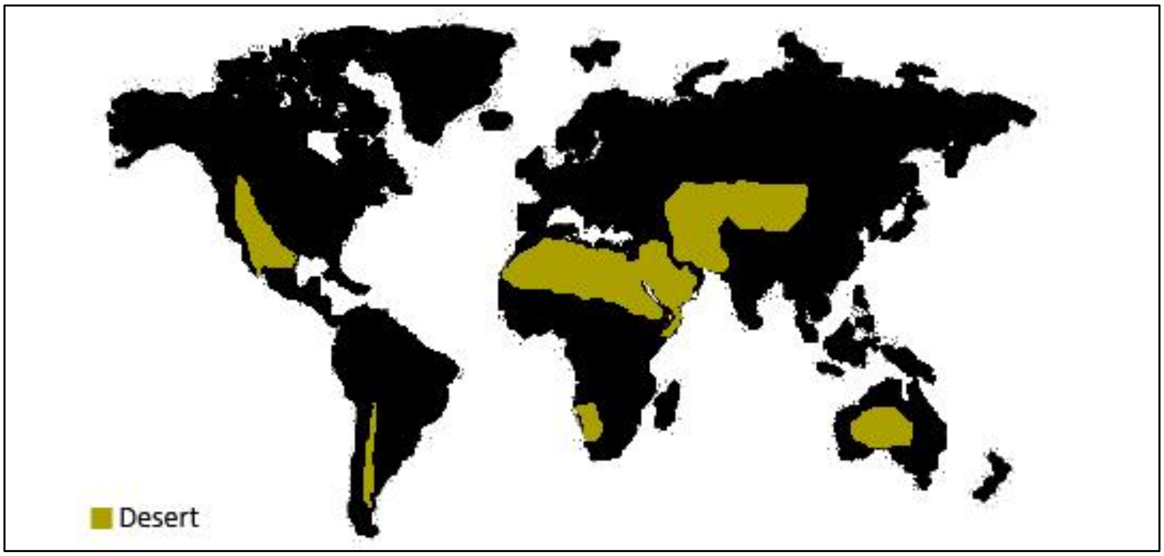

Figure 31: Map of Desert Biome in the World

9.2 Desert Plants Adaptations

How does such a harsh environment support life? The major environmental challenge in the desert is aridity, the deficiency of moisture. Desert plants are able to not only survive long periods without rain, but to thrive, through adaptations. Plants of arid and semi-arid regions take many forms. Each have their own way to ensure that prolonged periods of drought will not lead to dehydration and death. Some plants have developed tap roots that can extend thirty meters below the surface to draw water out of the water table while other plants have

[52] divya. "Plants and Animals Adaptations to the Desert Biome | Scienceray." Scienceray | All That is Science, Astronomy, Biology, Chemistry, Mathematics, Physics. http://scienceray.com/biology/ecology/plants-and-animals-adaptations-to-the-desert-biome/ (accessed March 1, 2010).

shallow roots to catch water as soon as it lands. To shield themselves from the blazing sun, some plants have spines or fur to reduce heat gain while others have small leaves to minimize surface area hit by the sun so that less water evaporates. There are also some species that close their leaves and keep them close to the stem to reduce water reduction during the day and then open at night to absorb moisture. Plants in the desert are usually spaced out from each other to prevent competing for water as it is scarce. Some plants also produce chemicals or poisons in their roots to keep other plants from growing or coming nearby.

Desert plants have adapted to the extremes of heat and aridity by using both physical and behavioral mechanisms, like desert animals. These mechanisms are classified into three types of drought resistance: drought tolerance, drought avoidance, and drought evasion.[53] Drought tolerant plants are characterized by their ability to undergo dehydration in their protoplasm without permanent injury to the plant. However, few desert plants have this property. Desert avoidance plants are known for their ability to resist water loss, increased water-uptake, and improved translocation of absorbed water. Stomatal closure, reduced cuticular transpiration, leaf modification, and moisture control are some characteristics of drought avoidance plants. Drought evasion plants are recognized by their short lifecycles. These plants usually live during the short rainy season, and pass the rest of the year in a dormant state.

Plants that have adapted by altering their physical structure are called xerophytes. Xerophytes, such as cacti, have special means of storing and conserving water. They often have few or no leaves, which reduce transpiration. Phreatophytes are plants that have adapted to arid environments by growing extremely long roots, allowing them to acquire moisture at or near the water table. Some desert plants have developed a lifestyle that corresponds with the seasons. For instance, perennials such as the ocotillo remain dormant during dry periods of the year and become active when water becomes available. After rain falls, the ocotillo quickly grows a new suit of leaves to photosynthesize food. Flowers bloom within a few weeks, and when seeds become ripe and fall, the ocotillo loses its leaves again and re-enters dormancy. This process may occur as many as five times a year. The ocotillo also has a waxy coating on its stems which serves to seal in moisture during periods of dormancy. There are also annual plants that live for only a season.

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[53] Cloudsley-Thompson, M J Chadwick J L. *Life in Deserts*. London: G T Foulis & Co Ltd, 1964. pg. 37

Plants are known for their ability to lose water at a very rapid rate by the process of transpiration. In an environment like the desert where water is limited, the ability for plants to reduce the rate of transpiration is a key to drought resistance. Morphological adaptations to resist water loss include a decrease in cell size, dense hair coverings, thickening of the cuticle covering the epidermis, an increase in the development of the palisade tissue in the leaf, stomata sunken into the leaf tissue, the appearance of well-developed hypodermal tissue and water parenchyma, well-developed sclerenchyma tissue to give increased mechanical support, and a closer more compact network of veins in the leaf.

Since roots take up water by passive diffusion, plants in the desert can absorb water only from soil wetter than their own moist interiors. Desert rains are often short, brief, and fast drying. Thus, plants in the desert must be able to absorb large quantities of water in short periods.

9.1.1 Cactus

In response to extreme habitats, cacti have developed special physiological traits and distinctive appearances that enable them to live and thrive in arid and semi-arid environments. Most cacti have adapted to living in dry environments in at least four ways: by photosynthesizing with their stems instead of leaves; by having spines that protect their stored water and photosynthate; by storing water, when it is available, in deeper tissues of their stems; and by using a water-conserving form of photosynthesis.

Cacti are among the most drought-resistant plants on the planet due to their absence of leaves, shallow root systems, ability to store water in their stems, spines for shade, and waxy skin to seal in moisture. Their extensive shallow root systems are usually radial, allowing for the quick acquisition of large quantities of water when it rains, and because they store water in their core of stems and roots, cacti are well-suited to dry climates and can survive years of drought on the water collected from a single rainfall. Many other desert trees and shrubs have also adapted to dry environments by eliminating leaves and replacing them with thorns or by greatly reducing leaf size to eliminate transpiration. Typically, a cactus possesses a perennial photosynthetic succulent stem bearing leaf spines produced on modified auxiliary buds called areoles. Spines protect cacti from animals, shade it from the sun, and also collect moisture. There are over 1,600 species in the Cactaceae family.[54] However, each species possesses similar

[54] Ibid. pg 1

characteristics that separate and underline their strong climate adaptability over other desert plants.

Generally, a plant thrives with more leaves because they contain small pores known as stomata that provide more surface area for the production of sugar via photosynthesis. However, the stomata also provide an exit route for the water vapor inside the leaf. Therefore, in the desert, very few plants possess a lot of leaves because a leafy plant would quickly exhaust its water reserves. The majority of cacti carry on photosynthesis inside their stems. This characteristic preserves their water resources, but limits photosynthesis efficiency, resulting in slow growth. A freshly hydrated plant stem is almost 100% water.

9.1.1.1 Ribs and Tubercles

Two cactus structures, the ribs and tubercles, help the cactus stem expand and contract as water availability changes. The ribs also help to channel water from rainfall to the roots and help to shade portions of the stem throughout the day. Many cacti stems have a globular shape for water storage. A globular shape is considered to be optimal because a globe maximizes volume while minimizing surface area. Minimum surface area keeps water losses through the stomata to a minimum. In some cacti, the water that is taken up into the stem is converted into mucilaginous substance that does not evaporate as readily as water and helps the cactus survive through the cold winter.

9.1.1.2 Rays

Rays in cacti are extremely variable in width and length, but are generally wider than in typical dicotyledons, an adaptation that facilitates water storage. Rays also function in the lateral movement of water. Stem strength is related to stem diameter and height. For instance, in some slender columnar cacti, the height of the stem may exceed the allowed diameter, which leads to mechanical failure of the stem. Increases in water storage tissue, especially in the cortex and wood, thickened cuticles, and the presence of a hypodermis are all well-known structural adaptations to dry environments.

9.1.1.3 Roots

Roots are essential for water uptake, mineral acquisition, and plant anchorage. These functions are especially important for cacti because of limited and variable soil. Root structural properties are fundamental to the ability of cacti to gather water and nutrients quickly, and to endure and recover from drought. Therefore, an understanding of the relationship between root structure and function is essential to understanding how cacti are able to occupy some of the driest, most nutrient poor habitats on earth.

Different types of roots can be classified according to their developmental origin. A root that develops from the embryonic radical is termed a primary root. Later, when the primary root reaches a certain length, lateral roots form. Any root formed on another root is considered a lateral root. However, when a root forms on an organ other than a root, it is termed an adventitious root at or near areoles. Cactus roots can also be classified according to their function and position within a root system. According to Carleton Preston from Harvard University, roots can be identified as either anchoring or absorbing roots in different cactus species based primarily on their vascular cylinder thickness.[55] Anchoring roots are then further divided by William Cannon from the Desert Botanical Laboratory into two types: vertically oriented, penetrating taproots and horizontally oriented, supporting roots. Meanwhile, absorbing roots are divided into two categories: rope-like roots and filamentous, relatively thin roots. Two other root types with morphological modifications are succulent roots and tuberous storage roots. Water-storage tissue in succulent roots has the ability to withstand a high degree of dehydration without irreversible damage, and may also help prevent water loss and decrease root shrinkage during drought. Another specialized root type is aerial roots, which are short, succulent, and sometimes extensively branched.

Root systems can be composed of several different root types and in many combinations. However, there are three basic patterns of root systems. The first type is composed of a taproot with few or no lateral roots. The second type of root system is composed of a taproot, horizontal subsurface lateral roots, and/or adventitious roots. The third type consists of roots of different lengths, with small species tending to have numerous branched roots directly beneath the shoot and larger species tending to have long subsurface roots extending some length from the shoot. Root elongation is essential for continued water and mineral uptake and the rate of elongation depends on temperature. For the barrel cactus, root growth in response to temperature can be described by a bell-shaped curve, with maximal elongation at 30˚C.[56] Boulders and subterranean rocks, which are common in desert environments, can provide favorable microsites for cactus root systems. For instance, lateral

[55] Ibid. pg. 44
[56] Ibid. pg. 45

roots of barrel cactus are five times longer and three times more numerous under rocks than in regions of the soil without rocks.

Most desert cacti can be classified as shallow-rooted perennials. The roots of most cacti usually grow no deeper than 15-20cm below the soil surface. The deepest roots are found from columnar cacti due to their height. In some cacti, shallow, extensive root systems can spread laterally ten to fifteen feet away from the plant to maximize water intake from a large area.

9.1.1.4 Areoles

Another distinctive feature of cacti is areoles. Areoles are independent structures that come in the form of either spines, hairs, flowers, fruits, or glochids (Figure 32). They are an important evolutionary modification for cactus because not only do they provide spines for protection, they produce spines of many different types to suit different needs. Some areoles produce radial spines that help to shade the plant and trap a layer of cool air next to the plant. Since the areoles are independent structures, the cactus stem will not damaged the areole is detached and water inside the stem will remain protected.

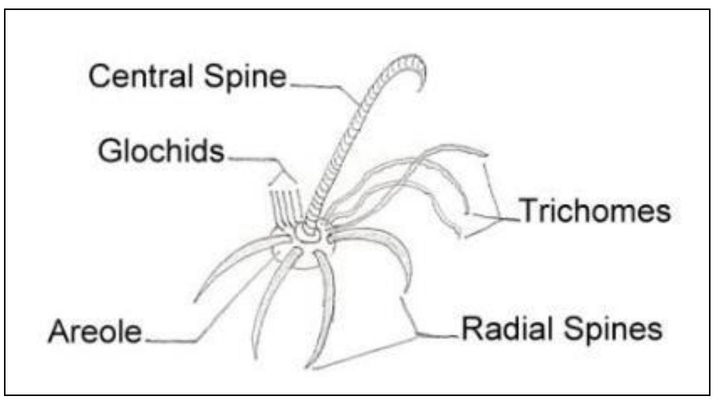


Figure 32: Cactus Areole Structures

9.1.1.5 Spines

Finally, spines play many important roles for a cactus. The most obvious role is protection against foragers. Some spines help to gather water while other spines point downward and help to direct rainwater to the roots of the plant. Some spines also help in evaporative cooling by reflecting sunlight away from the cactus stem and trapping a layer of cool air next to the cactus stem to lower the stem temperature and prevent loss of water.

9.2.2 Characteristics of Desert Plants

To gain a deeper understanding of cacti form and function, four different types of desert plants have been selected to illustrate the diversity of the plant and its versatility in harsh climate adaptation. Both the morphological and biological aspects of the plant are studied.

9.2.2.1 Creosote Bush

The creosote bush is one of the most successful of all desert species because it utilizes a combination of adaptations. Instead of thorns, it relies on a smell and taste wildlife find unpleasant for protection. It has tiny leaves that close their stomata (pores) during the day to avoid water loss and opens them at night to absorb moisture. The dimensions of its leaves are also considerably smaller than those of irrigated plants. The lower and mature leaves dry up and die when extreme drought conditions prevail. The small leaves of the buds, although drying out and turning brown, retain the power to continue growth when more favorable conditions return.

Figure 33: Creosote Bush and Diagram

The creosote bush exhibits considerable variations in morphology. It features exterior stem angles greater than forty-five degrees that trap no litter beneath the canopy (Figure 33).[57] In contrast, shrubs of this species with a growth form approaching hemispherical, accumulate subcanopy litter layers. The subcanopy soils of these plants have nutrient concentrations higher than the intershrub soils, forming islands of fertility. The protection provided by shrubs to the

[57] Whitford, Walter G.. Ecology of Desert Systems, First Edition. Toronto: Academic Press, 2002. pg. 103

soil surface beneath the canopy results in differential rain-splash. More sediment is splashed into the area under the canopy than is splashed outward.

9.2.2.2 Barrel Cactus

Barrel cactus, also known as ferocactus, meaning fierce or wild cactus, are cylindrical or barrel-shaped and are among the largest cacti of the North American deserts (Figure 34). They also are characterized by their parallel ridges that run down the sides with spines. For the barrel cactus, solutes decrease in the inner cortex and pith, lowering the osmotic pressure and thereby favoring the redistribution of water to the chlorenchyma.

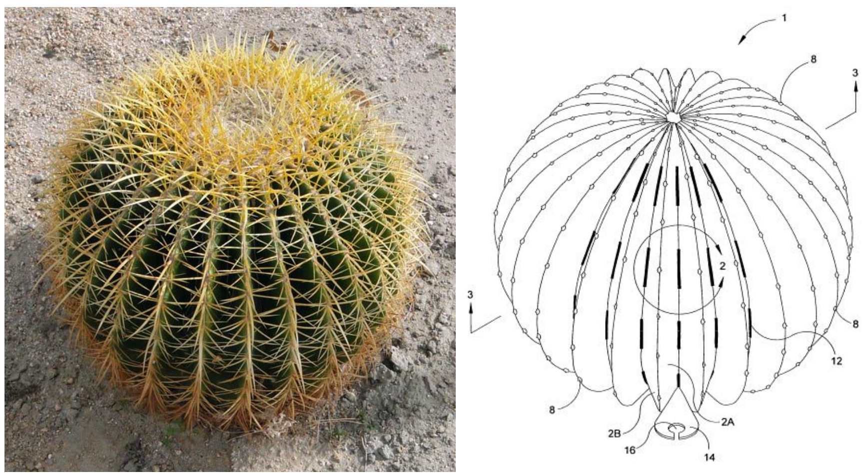


Figure 34: Barrel Cactus and Diagram

9.2.2.3 Brittle Bush

Brittle bush is a small deciduous shrub which grows as a low, roundish mound between two to five feet high (Figure 35). Brittle branches sprout from a woody trunk. The leaves have serrated edges and are broader at the base than at the tip. The leaves are covered with a thick mat of short hairs giving them a gray-green appearance. The hairs form a blanket over the leaves and act as an insulating layer against the heat and cold. They also help to trap moisture in the air and reduce the amount of water lost to dry air, thus, maintaining a cooler environment.

During drought, brittle bushes produce leaves which are highly covered with down or fine short hair. The amount of pubescence increases for each cohort of leaves produced during soil drying, and this reduces the absorption of incident solar radiation. In addition, increased pubescence reduces heat load, which helps maintain leaf temperatures while decreasing dependence on transpiration cooling for preventing high leaf temperatures.

Figure 35: Brittle Bush

9.2.2.4 Saguaro Cactus

Saguaro Cactus is characterized by its smooth and waxy skin that is covered by two-inch of spines (Figure 36). Its branches grow upright to collect and hold water when it rains. The ribs can absorb a lot of water because they can expand. The saguaro cactus also has a very elaborate root system. The plant has one tap root that is only about three feet long and two sets of radial roots. One is a thick root system, which is only about one foot long, and the other is a thinner root system that grows to a length equal to the height of the cactus. The Saguaro Cactus also has a very strong framework consisting of three different structural features. There is a woody tissue that runs parallel up and down the plant to form a cylindrical shape. There is also whitish pith and a fleshy tissue. Downward pointing spines make it easier to direct rainwater into the depressions of the cactus. The spines help to cool the outer skin. The spines also help redirect the wind and insulate the plant.

In an analysis of twenty-five species of North American columnar cacti, researchers from the Department of Botany from the University of Texas at Austin found that stem morphology and branching architecture is associated with variations in climate by a simple transition function for surface and volume relationships. Figure 36 is a diagram that illustrates how different forms are the result of different Fundamental Branching Templates (FBT).[58] In environments with cool winters, the stems of taxa are relatively thick and the plant will increase the coefficient value for stems and/or decrease in height. In warmer environments, stems are relatively thinner and taller. Similarly, in wetter habitats, the stems are tall whereas in drier environments, the stems are short and close to the ground. As a result of this study, an FBT is

[58] Cornejo, Dennis O., and Beryl B. Simpson. "Analysis of Form and Function in North American Columnar Cacti (Tribe Pachycereeae)." *American Journal of Botany* 84 (1997): 1482-1501. *Analysis of Form and Function in North American Columnar Cacti (Tribe Pachycereeae)*. Web. 15 Mar. 2010.

created to illustrate that variation in average winter temperature is associated with variation in stem girth and variation in average annual precipitation is associated with variation in stature and rate of branching.

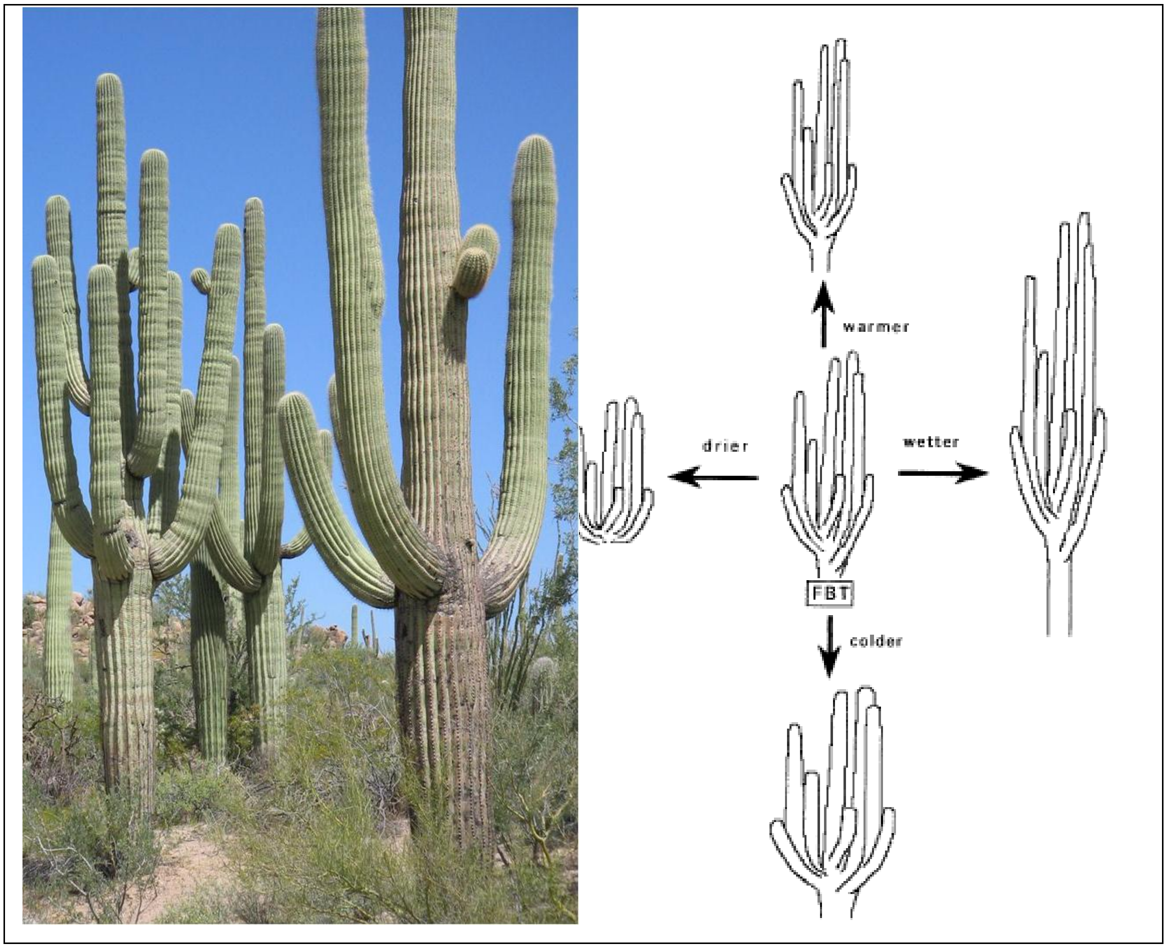


Figure 36: Saguaro Cactus and Diagram

9.3 Desert Animals Adaptations

The desert provides a particularly inhospitable environment for animal life. Yet, in the desert we find various creatures. Animals that have a relatively or completely impermeable body covering are found to be the most adaptive living organisms in the desert. Moist skinned animals such as earthworms, snails, woodlice, and centipedes are not particularly well adapted to arid conditions, but they manage to survive in such conditions by burrowing deeply into the soil.

Animals in the desert experience the same biological problems as all terrestrial animals: the ability to conserve water for vital purposes and to transpire it for cooling. In hot climates, survival depends upon avoiding dehydration and keeping cool. One of the most important behavioral adaptations of desert animals to hot, dry environments is the exploitation of burrowing habits. Due to their relatively small size, arthropods in particular depend largely on the practice of burrowing deep into the sand for survival in the desert. Though other larger animals like amphibians, reptiles, and mammals have evolved morphological mechanisms to adapt to the desert environment, burrowing behavior alone may sometimes be a sufficient adjustment for their existence in an arid climate. Lizards' and snakes' relatively impermeable skin helps to prevent transpiration. However, they too depend on a cool, humid burrow to reduce the rate of water evaporation. Terrestrial tortoises and turtles also show burrowing habits when they live in arid environments. Small mammals such as African jerbos and American kangaroo-rats avoid extreme temperatures and drought by living in burrows from which they emerge only at night.

Large animals cannot escape the desert by hiding underground. Therefore, they must either tolerate it or prevent excessive rises in body temperature. The amount of heat that reaches the body in a hot environment depends on the amount of insulation covering the surface. Fur is an advantage to desert animals in preventing overheating as it acts as a barrier to solar radiation. It also helps to slow down the conduction of heat from the environment to the animal. A camel's fur is a great example of such insulation. Since heat is bound where water changes from liquid to vapor, there is considerable advantage if the sweat evaporates at the skin surface without wetting the fur. If water evaporates from the skin surface, this is the coolest point in the system. The insulating dry fur is between the hot air and the cooler skin surface and therefore reduces the heat flow from the environment. If the fur is wet and evaporation takes place from its surface, the hot air has unimpeded access to the site of evaporation. The flow of heat from the body is now impeded by the intervening layer of fur. Figure 37 is a diagram illustrates the temperature gradients in the skin and fur of a camel. This means that much more water must be used to keep the site of evaporation sufficiently cool for the necessary heat dissipation.

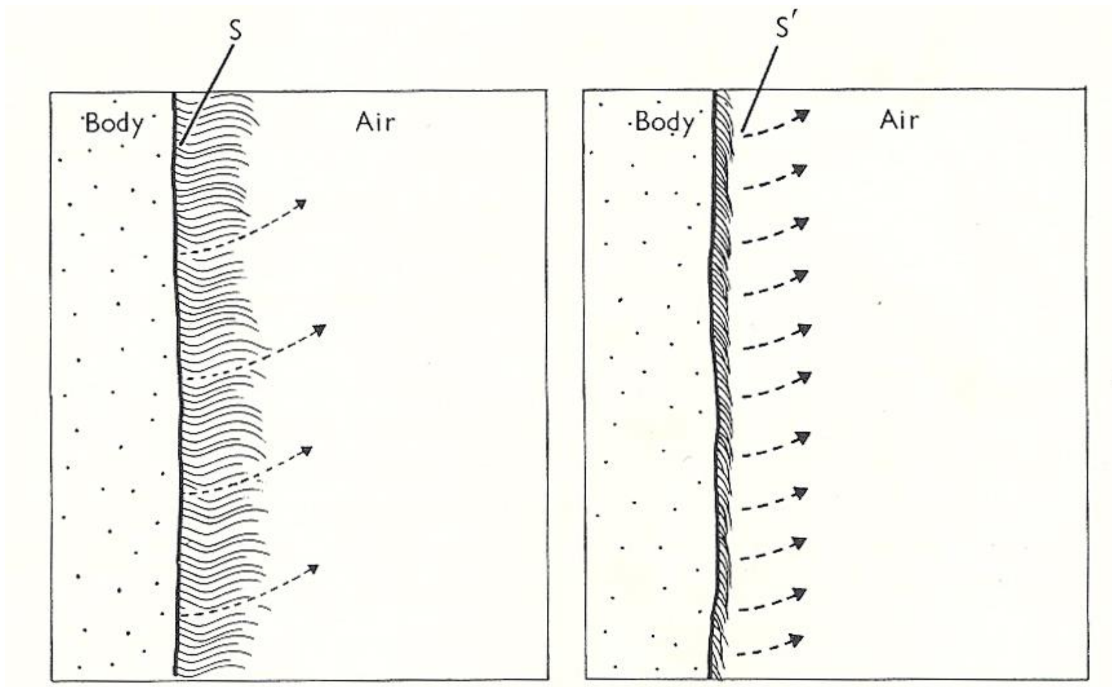


Figure 37: Fur Diagram-illustrates the temperature gradients in the skin and fur of a camel as indicated by the value of evaporation without having the fur wetted by perspiration. S indicates the surface of evaporation. Evaporation is indicated by broken arrows

Thermoregulation for organisms in the desert is dependent on their body colors. Dark color bodies heat at a faster rate than light color bodies because reflectance is lower and the rate of absorption of radiant energy is higher. Most animals in the desert are light in color. Lighter colors absorb less heat from the sun than those that are dark.

Color changes in reptiles are also associated with concealment or camouflage. Principles of camouflage have been developed through the study of animal coloration (Cott 1940); and they are summarized as concealment, crypsis, and masquerade. Concealment hides an object from view; with crypsis, the object resembles its background; while in masquerade, the object resembles a discrete non-edible object (Endler, 1981).[59] By blending themselves with the environment, animals can escape dangerous animals and predators.

9.3.1 Microclimate environment

Ambient temperature is important to living organisms because many of the chemical, physiological and physical processes upon which life depends are temperature-dependent. Organisms exchanged heat with the environment by conduction, convection, radiation, and

[59] Hansell, Mike. *Animal Architecture (Oxford Animal Biology)*. New York: Oxford University Press, USA, 2005.pg. 11

evaporation. For most day-active organism, the most obvious way of avoiding radiation is to keep in the shade. In addition, arthropods and reptiles are ectothermal, meaning their metabolic rates are low and most of their body heat is obtained from the environment. When their temperatures reach or exceed the optimum, they seek cooler microhabitats like burrowing in order to maintain a degree of thermal homeostasis. By burrowing, they avoid the extreme heat of the day.

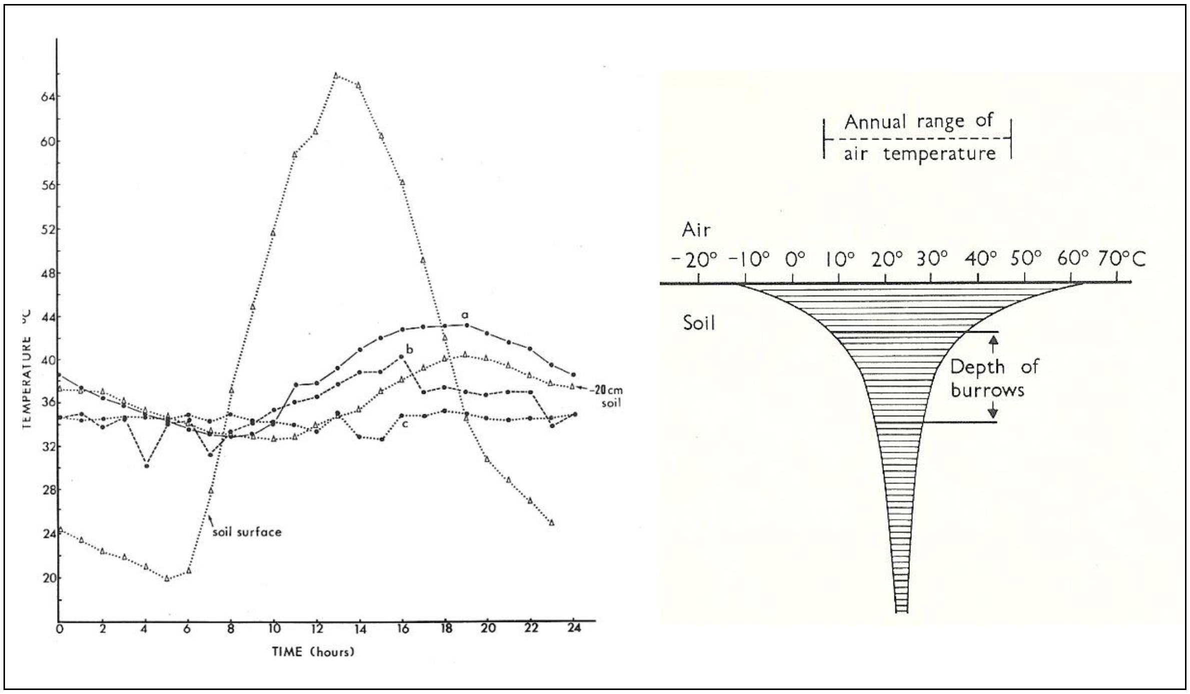


Figure 38: Thermal Significance of Burrowing in Arizona (right) and Burrow Temperatures of Scorpions (Left)

The thermal significance of burrowing deeply is further illustrated by the work of Hadley (1970b) who measured the daily temperatures sequences at various levels above and below an open desert surface in Arizona and the burrow temperatures experienced by free-ranging scorpions (Figure 38-R).[60] The temperature of the ground surface shows extreme variations. Although the soil surface temperatures fluctuated 46°C over a 24 hour period, the burrow temperature variations, some 20 cm below, did not exceed 10°C. Similar results were found in the study of tarantula and scorpion burrows, where the daily temperatures in the burrows only varied slightly as compared to the temperature fluctuation above ground. Desert subsoil temperatures measured in Arizona show that the surface temperature varies more than 80°F during the year, but the annual fluctuations at 1 meter depth are reduced to about 53.6 °F

[60] Cloudsley-Thompson, John L. Ecophysiology of Desert Arthropods and Reptiles (Adaptations of Desert Organisms) 1st Edition. Springer.1991.

(12°C) (Figure 38-L).[61] These data have been used by Misonne for a very instructive diagram as shown in Figure 40. In the Sahara, a similar range was found in sand. The annual variation at 1 meter was 52.1°F (11.2°C), the common depth of many animal burrows. The highest temperature hardly ever exceeds 86°F (30°C) in the burrows, which means there is no major heat stress. [62]

Another experimental study carried out in Morocco, Larmuth in 1978 also demonstrated that the temperature reached beneath a stone is dependent on its thickness and color, not on its horizontal dimensions. Color made a considerable difference in the temperature beneath a stone 2 cm thick, but with increasing thickness, color resulted in smaller differences. Thickness of a stone also affected the temperature registered beneath it. For example, grey stones shared a difference of 50.18 (10.1°C) between temperatures below thicknesses of 2 and 10 cm. Both sand and rock provide thermal protection in hot deserts. On the whole, rock temperatures fluctuate less than sand because rock surface tends to provide a more equal temperature than sand, and provides convenient pockets of shade.

9.4 Desert Environment Assessment

Deserts around the world are characterized by extreme temperatures and aridity. Considering how dry and hot a desert is, it is a miracle that life even exists in such environment. Plants and animals in the desert have adapted to the extremes of heat and aridity by using both physical and behavioral mechanisms.

Desert plants have three general categories of desert adaptations: drought tolerance, drought avoidance, and drought evasion. Plants have adapted to the arid environment with their unique physical structures. Cacti, one of the most drought resistance plants in the desert, have many characteristics that enable them to withstand extreme heat and aridity. Absence of leaves, shallow root systems, the ability to store water in their stems, spines for shade, and waxy skin to seal in moisture are a few of the many ways that cacti and other plants survive in the desert.

Desert animals have their own adaptations for the desert. Avoiding dehydration and keeping cool are their primary means of survival. One of the most important behavioral methods of keeping cool and preventing from dehydration is burrowing into the ground.

[61] Turnage, W.V. "Desert subsoil Temperatures", Soil Sci. 47, 195-9 (1939)
[62] "Water requirements of desert animals in the Southwest"., No. 107: 487-525 (1945).

This doctoral project is centered on the development of a new war shelter model for a desert contingency environment. Inspired by biomimicry, the study of how plants and animals acclimatize to the extreme desert environment can provide an alternative green design solution. Examining how plants and animals adapt to the desert and applying these methods to a design model may be a way to improve soldier comfort and protection in Iraq or other desert biomes in the world. Approaching the design with the goal of drawing from and integrating it with nature is a great opportunity to minimize the impact of greenhouse gas emissions.

PART III: DESIGN

10. DESIGN PROPOSAL

The design proposal is a synthesis of the research portion of the document and the biomimetic principles found in the study of how animals and plants adapt to a xeric environment. The result is an example of a war shelter design model inspired by nature that will offer comfort and protection for soldiers who are deployed to a desert contingency environment. An alternative approach to traditional environmental control systems like air conditioning is achievable by emulating natural forms, processes, and patterns in nature. In this case, the focus was on the adaptations of desert plants and animals in mitigating the extreme climate of the desert. The objective is to demonstrate the value of biomimicry in innovative and sustainable design solutions.

"The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone"-Janine Benyus

10.1 Design Intent:

There are four main goals for this project: first and foremost, to design a contingency military shelter based on biomimetic principles; second, to create a modular system as a way to improve the mobility, flexibility, and adaptability of the troop shelter construction process; third, to improve the comfort and protection of troops in a contingency environment; and finally, to minimize the effort and cost of transporting foreign materials into a war zone, which will reduce energy consumption and minimize greenhouse gas emissions. The ultimate goal is to design a model that is in harmony with nature. Figure 39 is an overall parti sketch that portrays the idea of how the design model blends in with the undulating sand in the desert.

Figure 39: Overall Design Concept Parti

10.2 Design Concept

Biomimicry is driven by the idea of finding natural solutions to human problems, so that our constructive world can be in balance with nature. Therefore, the overall concept of this project is blending with the desert environment. Biomimetic principles provide a means of being in harmony with nature while improving comfort and protection for soldiers (Figure 40).

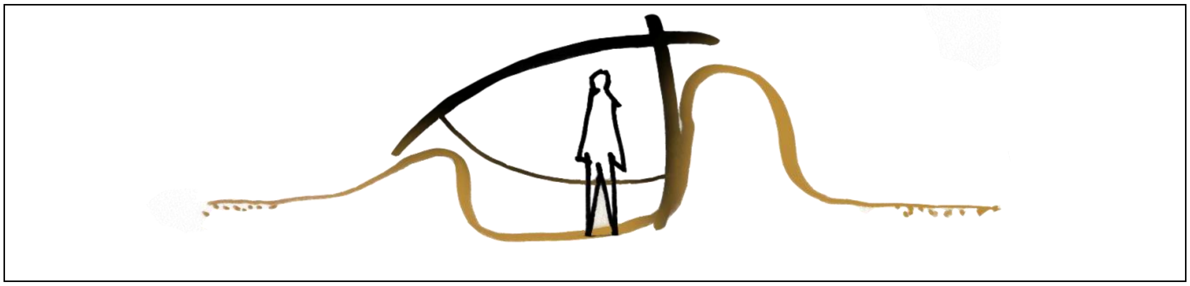


Figure 40: Model Parti

10.3 Design Framework

The design focuses on the adaptation of the model to a specific site and environmental condition as well as the standards of military construction for a contingency operation. The following paragraphs describe the various design parameters for the project in detail.

10.3.1 Site Parameters

Though site plays an important role in the development of a project, environmental and climate features are the driving force in this design. Based on many factors including the expanse of desert land mass around the world, the rising issue of global warming, and the frequency and potential of soldiers being deployed to desert-like environments, a specific site selection is not necessary as the parameters of the site are clearly stated. Given that one-fifth of the earth's surface is desert, the assumption is that the new war shelter model can be applied to any parts of the world considered desert environments.

10.3.2 Climate Zone

Hot and dry climates occur in latitudes 15-30 degrees north and south of the equator. They are characterized by a lack of humidity and seasonal changes in temperature, both of which can be attributed to land mass effects. Lack of water and high temperatures are what make this climate the most severe.

10.3.3 Climate Daily Pattern

The daily pattern is consistent most of the year. The lack of clouds and humidity means the sun is the main source of discomfort. Clouds act as a moderator in a more humid climate, shielding the land from solar radiation during the day and retaining heat at night. The absence of clouds creates more extreme conditions, with heat gain during the day being released at night.

10.3.3.1 Seasonal Pattern

The hot and dry desert climate is characterized by a clear cool season in July, with a summer season from November to March. Temperatures in winter are around 50°F (10˚C) at night and 86°F (30˚C) during the day. In summer, the night temperatures are around 77°F (25˚C), with a daytime temperature around 104°F (40˚C). Rainfall is low, with most falling December to March. Wind speed is low with occasional dust storms.

10.3.4 Desert environment

Desert biomes cover about one-fifth of the earth's surface and occur where rainfall is less than 50 centimeters per year. Desert biomes can be classified into four major types of deserts: hot and dry, semi-arid, coastal, and cold.

Hot and dry deserts are characterized by warm temperatures all year round and very hot temperatures in the summer. Rainfall is generally very low and/or concentrated in short bursts between long rainless periods. Evaporation rates often exceed rainfall rates. Some places may even experience years without rain. Hot and dry deserts experience daily extreme temperatures because the atmosphere contains little humidity to block the direct sunlight. Desert surfaces receive a little more than twice the solar radiation received by humid regions and lose almost twice as much heat at night. Mean annual temperatures range from 68-77°F (20-25˚C). Temperatures can reach as high as 95-120°F (35-49˚C) or as low as -60°F (-18˚C).

Soils are coarse-textured, shallow, rocky, or gravely with good drainage and have no subsurface water. Soils are coarse because there is less chemical weathering. In addition, finer dust and sand particles are blown elsewhere, leaving heavier pieces behind. Plants in this environment are mainly ground-hugging shrubs and short woody trees. Leaves are replete with water-conserving characteristics. They tend to be small, thick, and covered with a thick cuticle. In cacti, the leaves are often reduced to spines, and photosynthetic activity is restricted to the stems. Some plants open their stomata only at night when evaporation rates are lowest.

This project will focus on improving the living comfort of a war shelter, inspired by how plants and animals have adapted to the severe climate conditions of a hot and dry desert environment.

10.3.5 Program

Historically, soldiers work, eat, and bathe separately from their living quarters. Therefore, the main function of the space is living and sleeping. Soldiers eat primarily at dining facilities or other food concessions installed at each contingency base, thus a place to cook and eat is not included in the program. Finally, due to the restricted amount of living space available on base, showers and toilets are proposed to be separate from the living space. Additional space is provided for the purpose of personal belonging and equipment storage. The design model is based on a one to two-person shelter that could be grouped with others to form a larger living unit or community space.

10.3.6 Size:

Based on the Design Criteria Standard established by the Department of Defense, the recommended average square footage per person in a contingency living area is 80 square feet. Thus, 80 square feet is used as the base guideline for this design. The military always emphasizes the buddy system, in which two soldiers are always together to watch out for one another. Therefore, the design is also based on the concept of a pup tent, where two individual shelters come together to form a larger space. Unlike the pup tent, each shelter is also designed to stand alone as a living unit.

10.3.7 Standards of Construction:

The standards of construction are based on the expected duration of the contingency operation. Standards of construction for a contingency base are as follows:

Contingency Phase

- Organic (0-90 days)
- Initial (0-24 months)
- Temporary (6 months to 5 years)

Enduring Phase

- Semi-permanent (5 years to 10 years)
- Permanent (10 years and more)

The different phases of a contingency base are group into two general categories contingency and enduring. To further narrow the scope of this project, the design will focus on the contingency phase of construction, which is categorized into three distinct periods: organic, initial and temporary.

10.4 Design Models

The design models that served as the basis and inspiration for this project design include a list of biomimetic case studies and in-depth research on desert plants and animals. Rather than mimicking one specific plant or animal, which might result in a lost opportunity to explore broader ideas for a new war shelter, the research focuses on general characteristics of plants and animals that have adapted to the extreme desert environment. Through an in-depth study of plants and animals in the desert, nine biomimetic principles emerged. These nine biomimetic design principles provided the initial concepts for the new war shelter design model. Below is a brief description of each principle extracted from the adaptive characteristics of desert-dwelling plants and animals and their applications to architecture.

10.4.1 Biomimetic Design Principles

1. Less Surface Areas

The majority of cacti do not have leaves because the more leaves they have, the greater amount of surface is exposed to sunlight. Water in the desert is too precious. Plants need to retain their water resources as long as possible. Minimizing the surface area of the plant is one method of retaining water. For this reason, most cacti have thick stems and ribs, but minimal leaves. Similarly, the less building surface exposed to the sun, the cooler the interior space.

2. Thicker Envelope

The epidermis, or outermost layer, of the cactus is thicker than that of typical plants. The epidermis is the layer where all exchange with the environment occurs. The thick layer of the epidermis keeps the plants cool and helps to minimize the rate of water evaporation. To keep the interior space cooler, another alternative is to have a thicker wall.

3. Canopy Greater than 45° Conserves and Preserves Water

Creosote bush demonstrates how the form of a canopy can serve as a way to conserve and preserve water for life support. If a canopy angle is greater than 45 degrees, a plant is able to catch more water due to less rain splash. Meanwhile, the spread of the canopy helps to cool the ground and preserve the water content in the plant and soil for a longer period of time. This specific characteristic of the plant is essential for the survival of the plant in a xeric environment. This unique characteristic could be apply to a water catchment system to maximize the amount of water collection

4. Variation of Volume and Form in Relation to Climate Change

The form and volume of a Saguaro Catcus is dependent on the climate of its locality. The warmer the climate, the taller and thinner the plant becomes. In contrast, the colder the climate, the shorter and thicker the plant is. In a hot climate condition, the plant tries to reach higher to get more wind. Meanwhile, in a drier climate environment, the plant stays low to the ground, whereas in a wetter climate, the plant remains off the ground. This same volume and form relationship to climate can be use to maximize the amount of air movement within the space.

5. Parallel ridges

The parallel ridges of the barrel cactus serve two functions. Expansion and contraction help to conserve water, enabling the plant to survive in a xeric environment for a longer period of time. The ridges of the plant also serve as a shading and cooling device, making life possible in a dry and hot climate setting. This characteristic can be easily applied to the design of a building, thereby minimizing heat gain.

6. Material as a Form Protection and Heat Reduction (Spines)

Spines found on many cacti do more than protect the plant from getting eaten or damaged by animals. Different orientations of spines assist in cooling the plant by acting as a shading device. A similar material can be applied to the exterior of a building to serve as both a protecting and shading layer.

7. Burrowing

Life in the desert would not possible for many creatures like earthworms, snails, and centipedes if they could not burrow into the ground. By burrowing, organisms can avoid the extreme heat of the day. Similarly, if the module can be partly underground, heat gain can be reduced significantly.

8. In-between Space

Fur in a desert does beyond keeping the animals warm from the cold, it also help them to cool off during hot periods of the day. The study of temperature gradients in the skin and fur of a camel demonstrates the idea of heat flow through evaporative spaces. Evaporation from skin surface as opposed to fur requires less water to keep the body cool. Simply adding an in-between layer within the structure can help to reduce the amount of heat gain within the space.

9. Color Changes as a Form Concealment and Thermoregulation.

Desert animals change the colors of their bodies to adapt to the heat and to protect themselves from being attacked or eaten by other animals. Therefore, the color of a building material can do more than just regulate temperature; it can also serve as a form of protection against danger. Color changes enable animals to adapt to different environments at different times of the day and year.

10.5 Design Exploration

The design began with a series of sketches drawn in an effort to understand the nine biomimetic principles identified in relation to architecture. Following the biomimetic sketches was the development of two charts that illustrate how the biomimetic principles are applicable to the design and the different phases of construction in a contingency environment.

The initial design exploration was inspired by the biomimetic idea of burrowing to create a cooler environment below the ground surface. By simply digging into the land, reclaiming the use of excavated soil as a material, and adding a canopy, one can create a living space. Inspired by the biomimetic idea of expansion and contraction, I came up with the idea of a retractable roof system. A progression of burrow and canopy studies were then explored.

Figure 41 provides an initial study of translating the nine biomimetic principles into architectural expressions. Each principle is represented in a series of diagram that illustrates its characteristic impact in design.

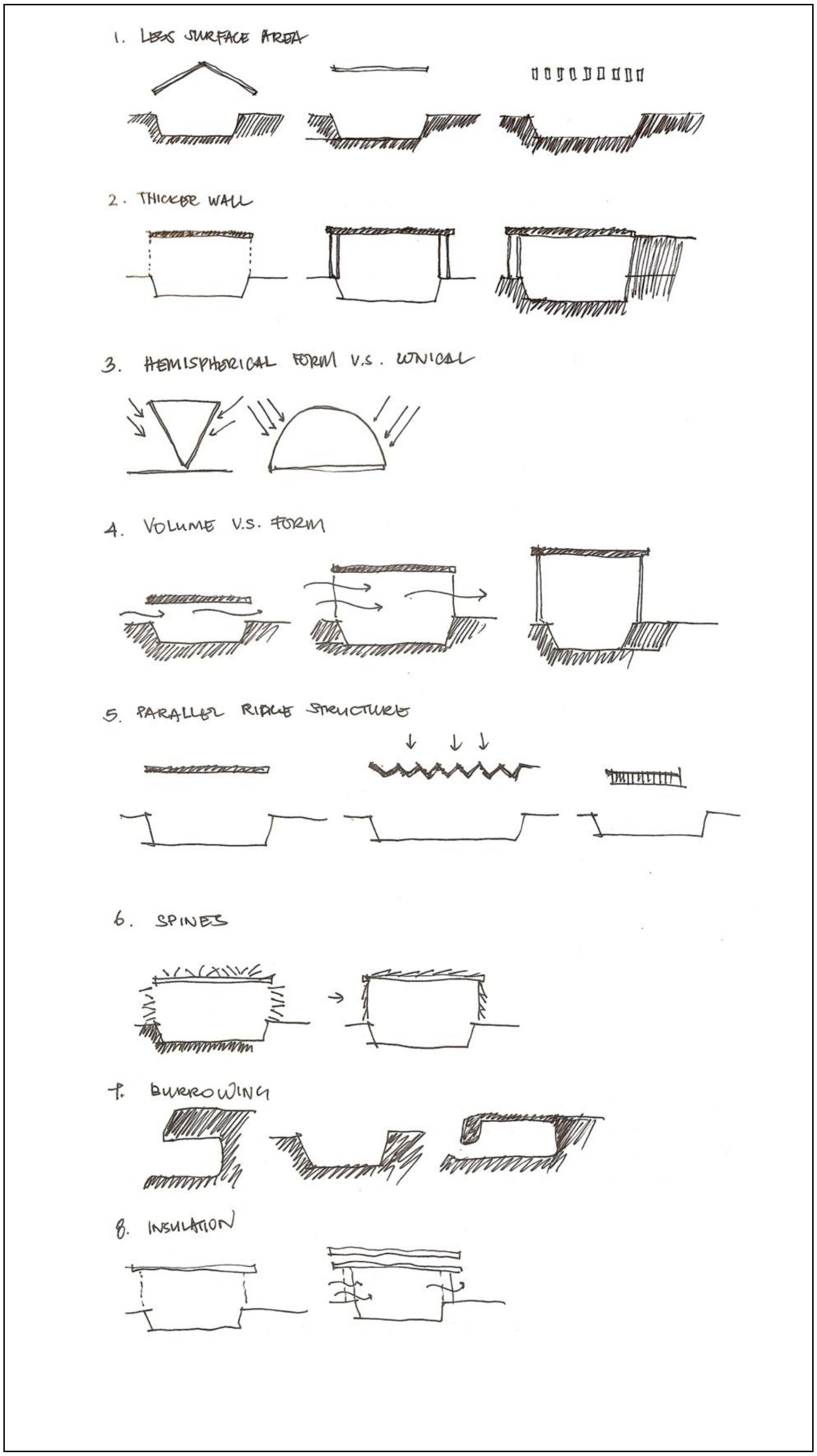


Figure 41: Biomimetic Principle Diagram Sketches

10.6 Design Methodology

Biomimicry Design Spiral is a tool suggested by the Biomimicry Institute to guide designers through the process of designing based on biological models. Represented in the form of a spiral, the tool illustrates the repetitive nature of the design process. After solving one challenge and evaluating how well it meets the biomimetic principles, another challenge often arises, and the design process starts all over again. The Design Spiral is characterized by six key concepts: Identify, Interpret, Discover Abstract, Emulate, and Evaluate.

The design methodology of this project is based on these key concepts along with some personal interpretations that were discovered along the design process. Personal experiences in Iraq follow by the inspiration of biomimicry initiated the exploration of this project. The next step was to identify the issue by recognizing the specifics of the problem in what the design needs to accomplish and to determine the design function. In this case, the issues addressed here are the comfort and protection of troop housing in a desert environment and the impact of greenhouse gas emissions on global warming. The design function is to create a new war shelter model. The next step was to interpret how and where the design problem can be resolve through nature. Desert plants and animals have learned to adapt and thrive in a desert environment for millions of years. A housing type in the desert can mimic the characteristic of how these living organisms mitigate such harsh climate conditions. Following the interpretation process is to discover and find the best natural models that are challenged by the same problem through in depth researching and data gathering. This project looks into the extremes of a desert habitat. Then the next step is to abstract the most relevant strategies to the design challenge. Nine biomimetic principles were abstracted from the studies of desert plants and animals. Then the next challenge is to emulate by developing ideas and solutions based on the biomimetic principles. A design matrix was created as a result to formalize the correlation between the biomimetic principles and the design challenge-comfort and protection. The second to the last step is to apply the principles to the design. Appropriate biomimetic principles were selected based on different phases of construction. The initial idea of burrowing led to the design of a modular panelized roof and wall system that meets the basic requirements of a war shelter model. The last and final step is to evaluate through computer modeling and simulation and a comprehensive comparative analysis. Part of the evaluation process is to not only assess the outcome of the design, but to identify further ways to improve the design and discover new inspiration. Hence, biomimicry is a continuing design process because nature will constantly evolve to fit into the changing environment around them. Figure 41 is an overview of the biomimetic design methodology used in this project.

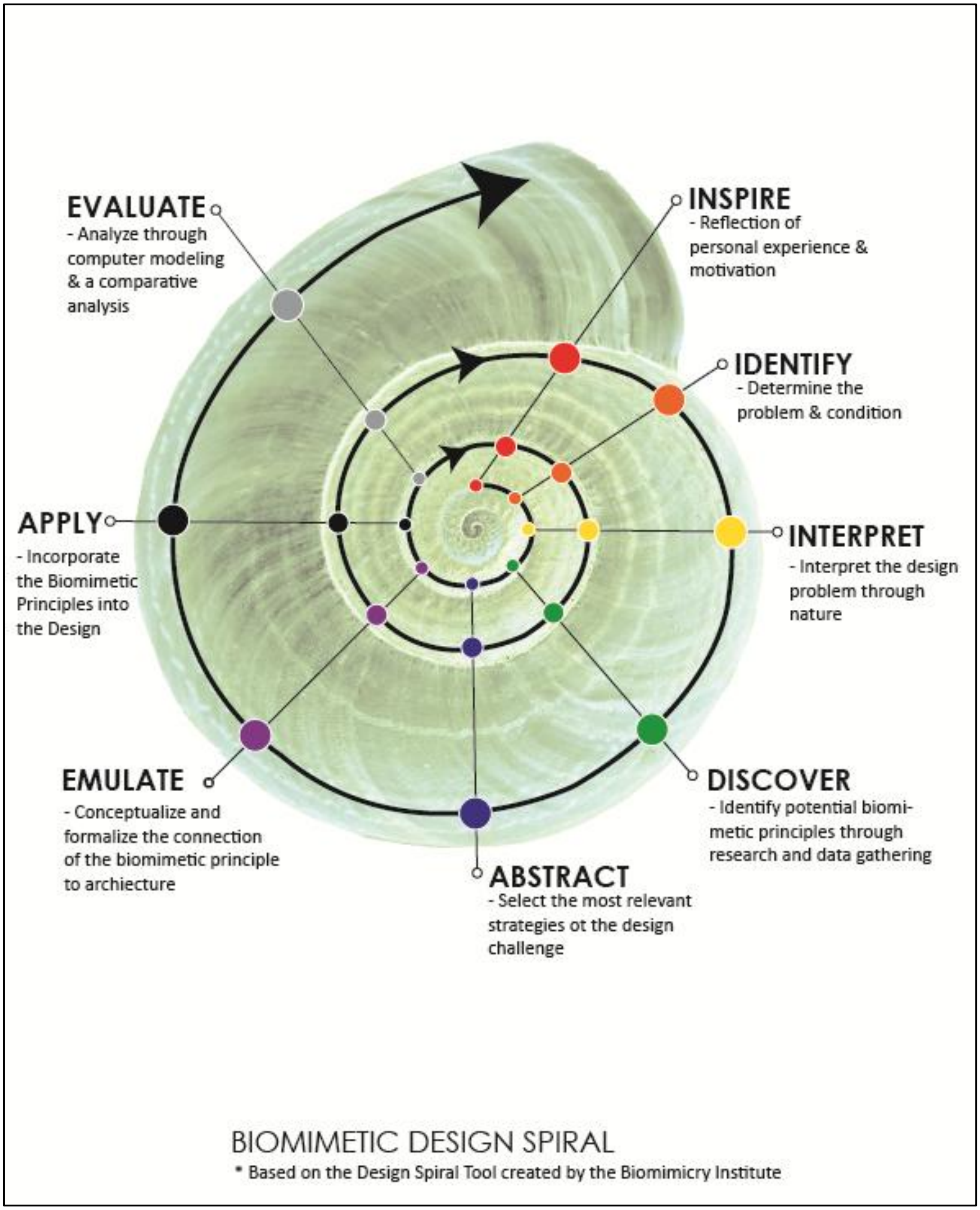


Figure 42: Overview of Biomimetic Design Methodology

10.6.1 Biomimetic Design Matrix

The nine biomimetic principles extracted from a study of plants and animals that live in the desert provide the basic concept of the new war shelter. To further understand how these nine biomimetic principles are related to architecture, a biomimetic design matrix was developed (Table 8). The matrix illustrates how each of the biomimetic principles can be applied to architecture in terms of comfort, protection, and green strategy. For instance, less surface area achieves comfort through heat reduction, provides protection by minimizing identification, and is a cost-efficient green strategy because it minimizes the use of materials. To further demonstrate how the principles can be applied to the evolution of a design, the biomimetic principles are translated into architectural expressions as illustrated in Figure 41.

BIOMIMETIC PRINCIPLES	COMFORT	PROTECTION	GREEN STRATEGY
Characteristics of how plants and animals mitigate extreme temperatures in a desert environment	Comfort from heat reduction, shading, and ventilation	Protection from external forces and identification	Cost-Energy Saving Solutions
1. LESS SURFACE AREA	Heat Reduction	Identification	Cost-Efficient
2. THICKER WALL	Thermal Regulation	Offers Strength	Energy Reduction
3. CANOPY GREATER THAN 45°	Shading	Weather	Conservation and Preservation
4. VOLUME & FORM	Ventilation	Form; Blending with the environment	Air Flow
5. PARALLEL RIDGES	Shading and Cooling	Structural Strength	Conservation
6. SPINES	Shading	Defense Attack	Energy Reduction
7. BURROWING	Heat Reduction	Earth	Natural
8. IN-BETWEEN SPACE	Evaporation	Weather	Conservation
9. COLOR CHANGES	Thermal Regulation	Concealment	Energy Reduction

Table 8: Biomimetic Design Matrix

10.6.2 Phases of Construction

The intended lifespan of a war shelter is dependent upon the duration of the operation. There are two categories of construction standards based on the anticipated lifespan of the base: contingency and enduring. This project focuses on the contingency category, which is governed by three subset standards: organic, initial, and temporary. During the lifecycle of each phase, the structure may be progressively improved to meet living standards and operational missions. To understand and illustrate the development of war shelters in a contingency operational environment, a construction category chart was generated (Table 9). Several biomimetic principles are used to determine the ideal construction for each category. An assumption has been made that during the organic phase, burrowing and a simple roof structure is the most appropriate. Following the organic phase is the initial phase, which requires a thicker enclosure and an expandable roof structure. As time progresses, the structure can be modified and grouped with others to form larger and more permanent structures.

PHASES OF CONSTRUCTION IN A CONTINGENCY ENVIRONMENT

CATEGORY	DURATION	PAST	PRESENT	FUTURE
ORGANIC	1-90 Days	Shelter Half	Unit Tents	Burrowing + Simple Canopy
INITIAL	Less than 6 months	Tentage	Organic Tentage with wooden floors/Tier I &II Tents	Expandable Roof Structure + Thicker Enclosure
TEMPORARY	6-24 months	Nissen/Quonset Hut	Tier III Tents/SEA huts/ Containers	Modify roof structure + Expandable units

Table 9: Phases of Construction in a Contingency Environment (Past, Present, Future)

11.6.3 Biomimicry Inspirations

A driving component of the design is the idea of burrowing, a common strategy for the mitigation of extreme heat in the desert. In the case of this design, the sands excavated from the burrow are a major design component. The burrow is not only used to reduce heat, but also as a readily available source of site material for protection, structural support, ventilation, and shading. Burrowing onsite and simply bringing in a roof structure to complete the space minimizes the use of fabricated materials and reduces the import of foreign goods.

The epidermis or outermost layer of cactus and other desert plants is thicker than that of typical plants. The thick skin helps to minimize the rate of water evaporation, which in turn helps to cool the plant. Therefore, having a thicker wall will help to cool the interior space. The sand excavated from the burrow can be used as a material to create berms around the model to reduce the transfer of heat, cool the space, and maximize prevailing wind direction.

One of the most recognizable characteristics that enable plants to survive the extreme heat of the desert is minimized exposed surface area; plants in the desert either have no leaves or tiny leaves. Plants in the desert also vary in height and weight based on the climatic condition of the site. For instance, in a drier climate, the saguaro plant stays low to the ground to mitigate the extreme heat of the desert. Thus, staying low to the ground and maintaining a simple roof profile are two characteristics of the new war shelter.

Creating a ridged roof profile and overlaying it with another sheet of canvas-like material mimics the idea of the in-between space found in my studies of camel fur and cactus spines. The canvas acts as a barrier to solar radiation and helps to slow down the conduction of heat, which in turn helps to cool down the interior space and makes the living space more comfortable. Like the ridges on a barrel cactus, the parallel ridges on the panel also stabilize the structure.

In a wide open area like the desert, skin color serves as a major thermoregulator. In addition, skin color serves as a form of concealment from predators. Therefore, the model mimics the typical color found in desert plants and animals.

10.6.4 Initial Design Exploration

Figure 43 illustrates how the different biomimetic principles can be applied to the three construction phases in a contingency environment. The initial attempt was to apply as many of the biomimetic principles to the design as possible. The biomimetic principles were treated as a series of improvements to the design. As the duration of the deployment is extended, various biomimetic principles are used to enhance either the space or structure of the design.

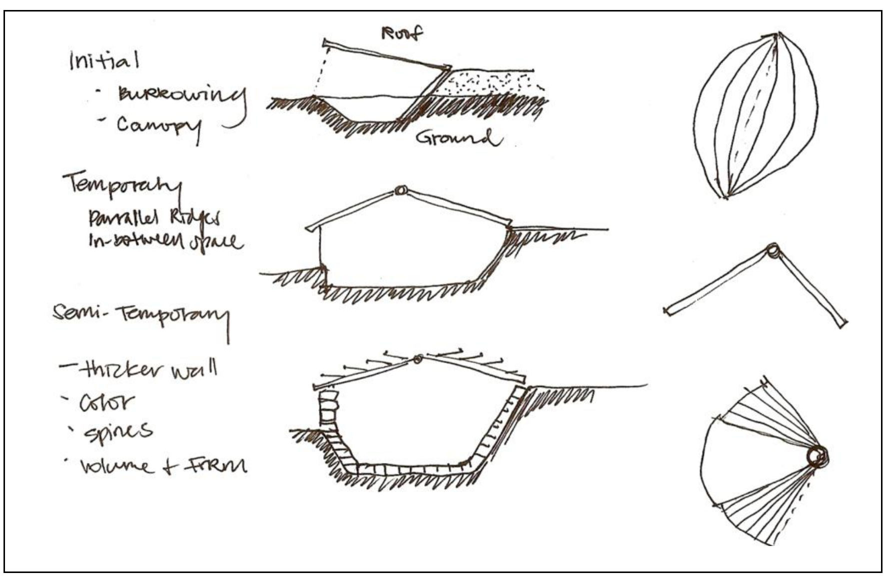


Figure 43: Initial Exploration

10.6.5 Burrow Studies

Inspired by desert animals' strategy of burrowing into the soil for heat mitigation, a significant amount of time was spent on determining the form and shape of the burrow. Figure 44 shows the initial exploration of the burrow form in relation to the canopy. Initially, the form was very rectilinear and symmetrical. As the design progressed, the burrow became more asymmetrical due to the use of the excavated sand.

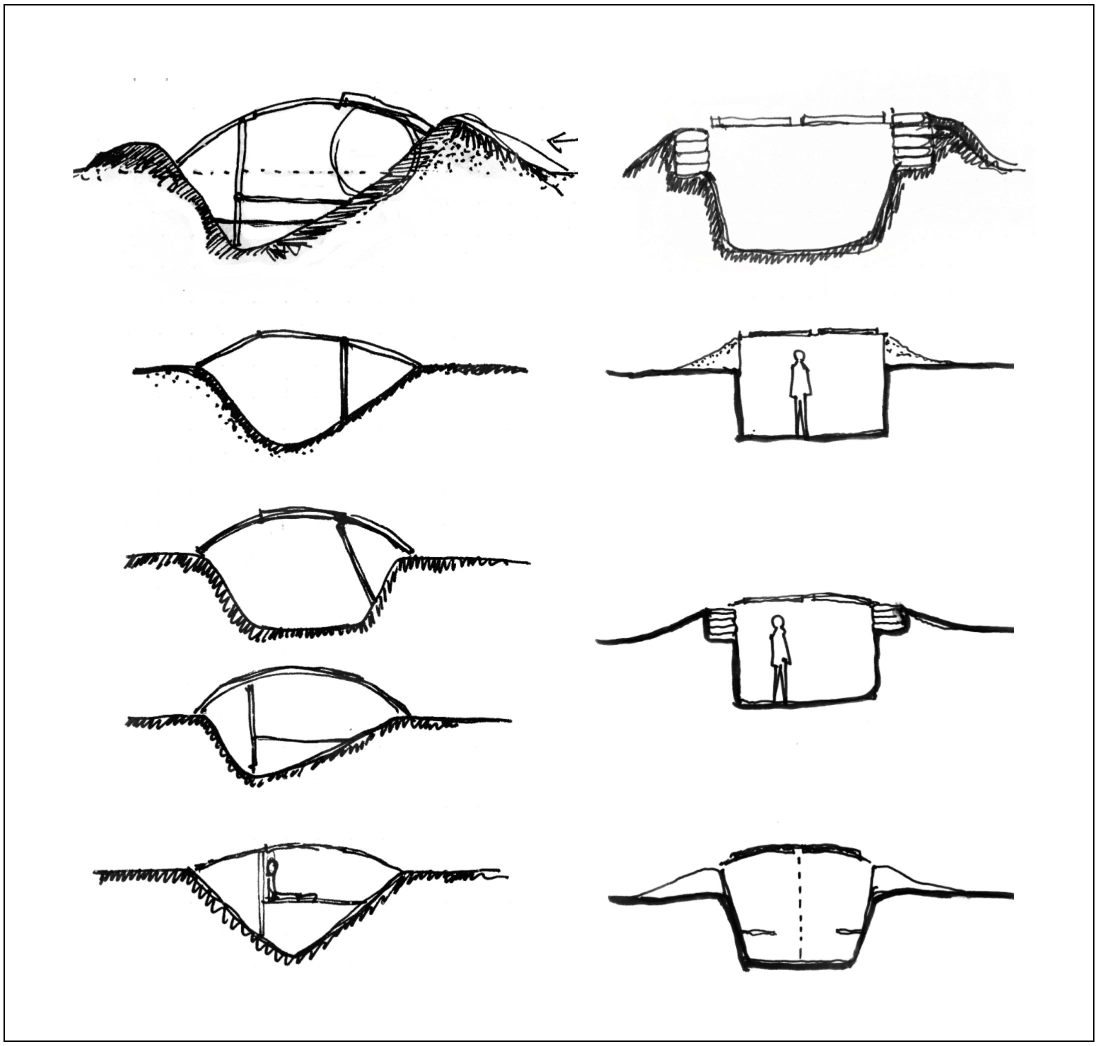


Figure 44: Initial Burrow Study Sketches

10.6.6 Study Models

Aside from sketches, a series of study models were constructed to understand the process of burrowing and the form of the canopy. Study model 1 represents the idea of a retractable panel wall and roof system. Study model 2 explores the use of sand and the placement of the berms. Study model 3 is a refined idea of the canopy and the use of sand as protection. Figure 45 represents the three study models discussed.

Model 1 Model 2 Model 3

Figure 45: Study Models

10.6.7 Use of Sand

The significant amount of sand that will be excavated to create the burrow effect offers a great design opportunity. The excavated sand can be used to reinforce the floor and wall, provide shading, direct wind flow, offer greater perimeter protection, and act as a form of concealment. Figure 46 illustrates an initial concept for the potential use of sand.

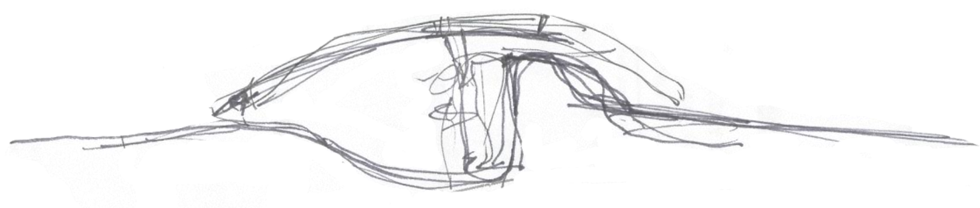


Figure 46: Initial Berming Sketch

10.6.8 Site Orientation

Excavated sand can also be used to orient the shelter based on different site conditions and situations. When facing the front line, the berm can be thicker and higher. Depending on the direction of the prevailing wind, the berm can be lower to improve air circulation within the space. The berm can also serve as an entry identification. Figure 47 represents some initial ideas for using the berming strategy to create a form entry.

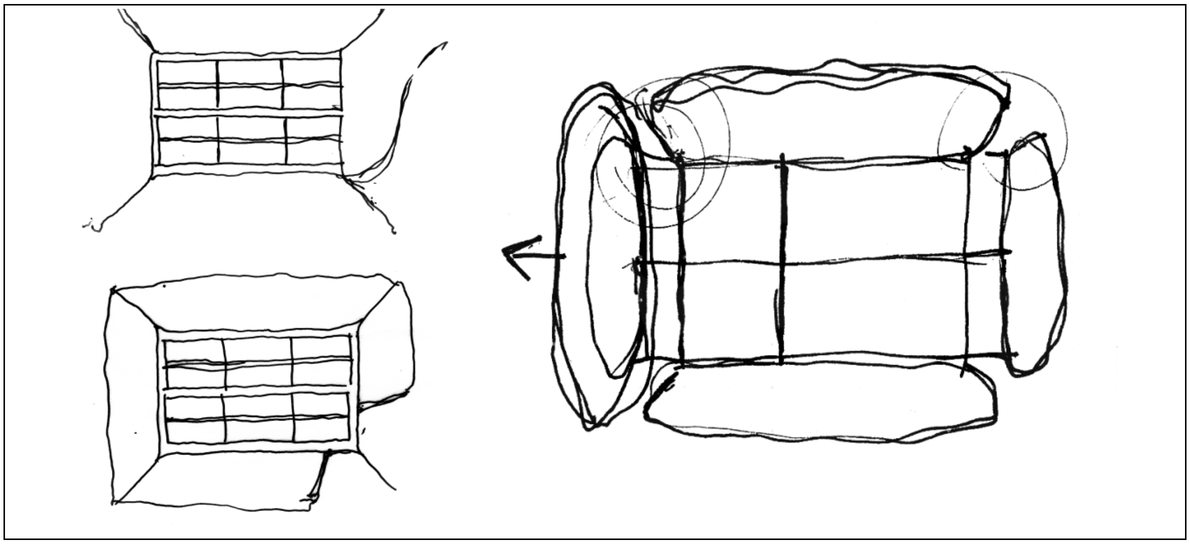


Figure 47: Berm Sketches

10.6.9 Canopy Studies

The canopy of the design is inspired by the barrel cactus' unique characteristic of expanding and contracting to conserve water as a key survival strategy in a xeric environment. The idea that the canopy could expand and contract led to the proposal of a retractable roof. Figure 48 illustrates the initial sketches of a retractable roof system. Figure 49 shows the initial section exploration of the expandable roof feature.

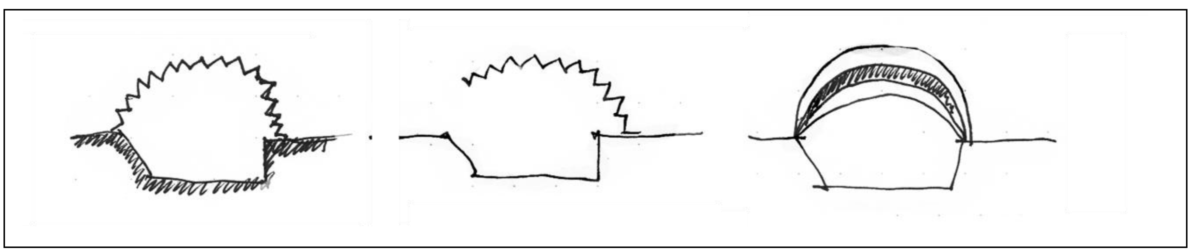


Figure 48: Initial Canopy Design Inspired by a Barrel Cactus

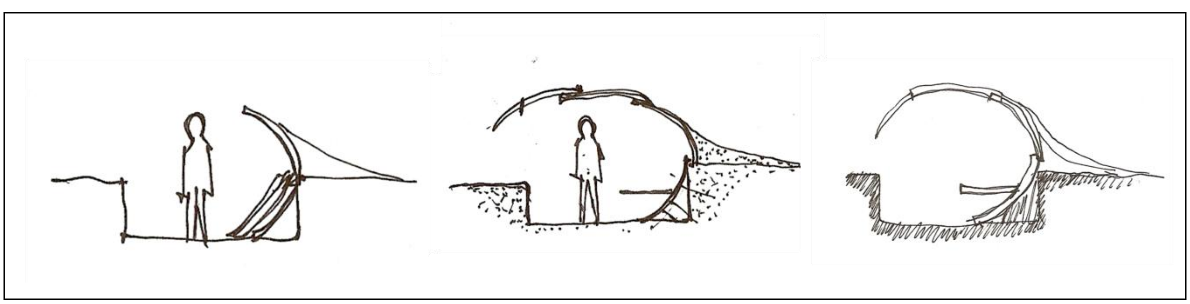


Figure 49: Section Exploration

Since the design is meant to work with the buddy system in which each person is provided with the essential equipment to construct his or her own shelter, a portable retractable roof system was considered. Prior to mobilization, each soldier would be issued a rucksack containing an expandable roof system. Once grounded, the retractable system could be expanded to create a canopy that provides full coverage and shading. Figure 50 illustrates a 3 feet by 3 feet panel system relative to the proportions of a human being.

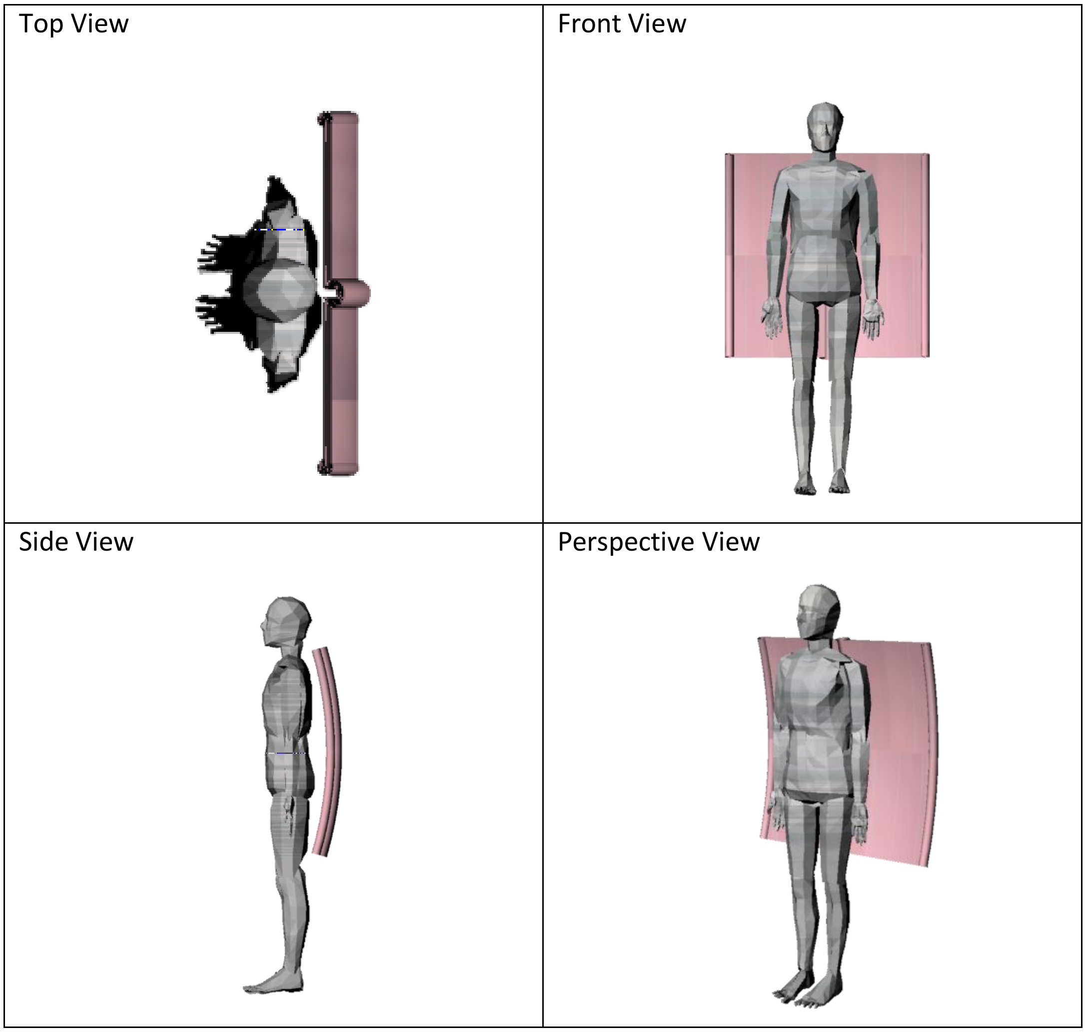


Figure 50: Portable Panel Roof System

10.6.10 Construction Process

Since the burrow is created onsite, the retractable roof is the only piece that must be brought onsite to complete the space and provide an initial shelter for a soldier. For this reason, the construction process plays an important role in the design process. Figure 51 represents the initial idea of the construction process of a retractable roof system. The benefits of having such system include the ease of mobility, assemblage, and the minimal use of materials. However, the design is very limited in size and flexibility. Therefore, the idea of a backpack roof system was discarded. Meanwhile, mobility and transportability are important elements of the design; as a result, the idea of a modular expandable panelized system continues to be explored.

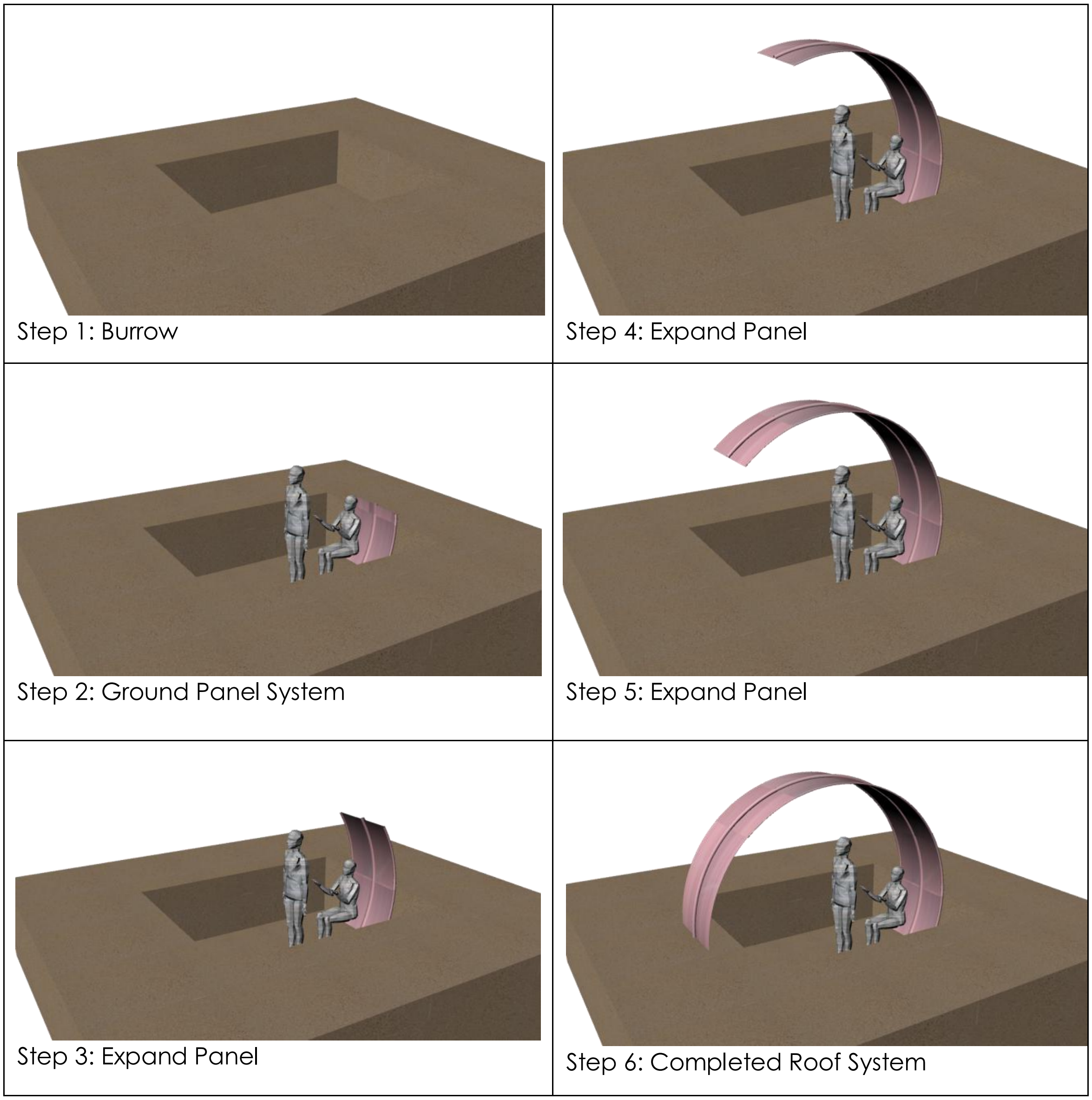


Figure 51: Initial Portable Panel Construction Process

An alternative method was used to explore the construction and form of the burrows. Figure 52 illustrates the transformation of the burrow form. As the design progressed, the construction process also became clearer. Figure 53 represents a more refined and detailed outline of the construction process. Excavated sand provides a great design opportunity. The soil can be used to berm around the perimeter and can be put into sandbags to reinforce the roof structure and serve as a finish for the wall.

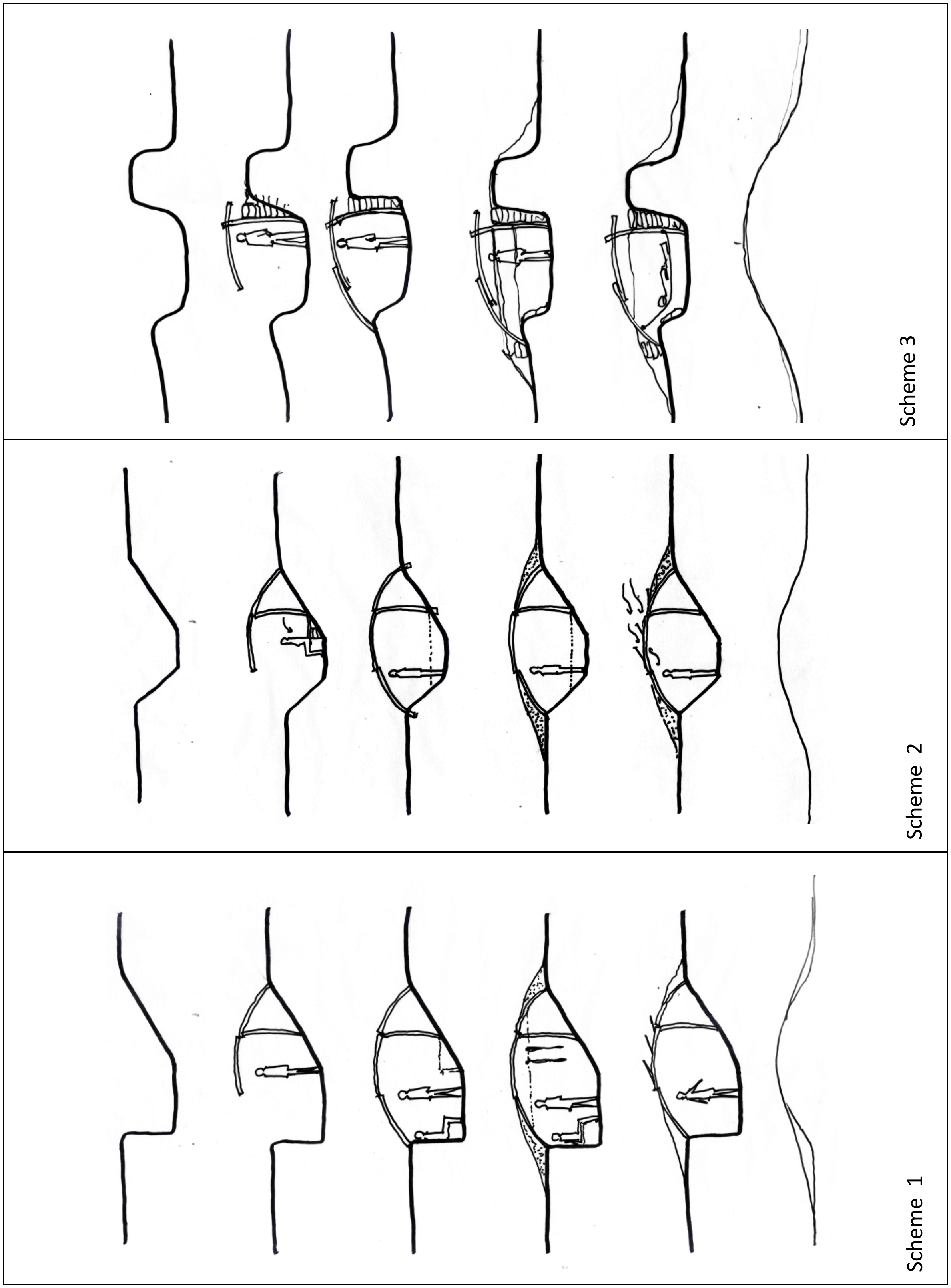


Figure 52: Burrow Development Process

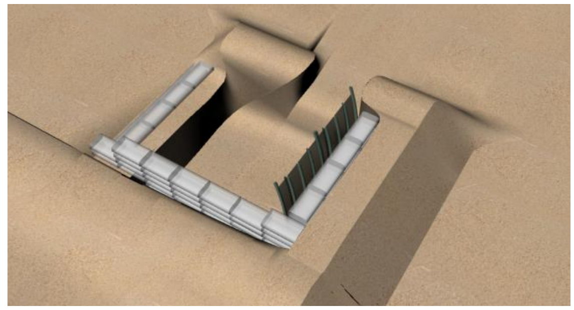
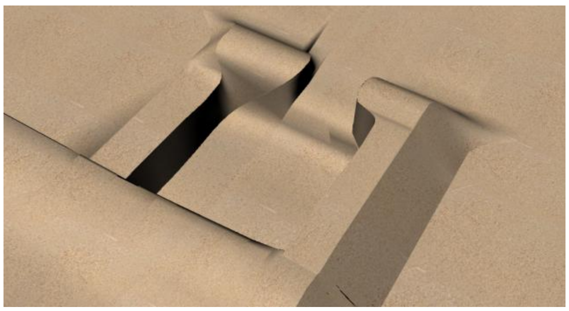
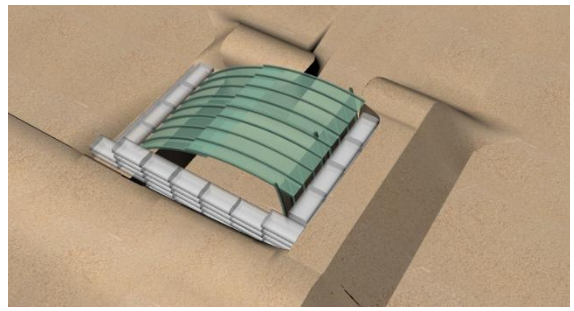
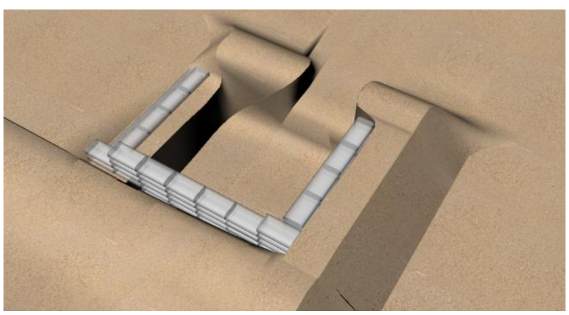
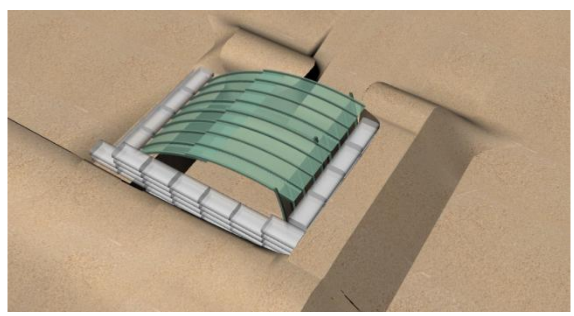
Step 1 	Step 4 
Step 2 	Step 5 
Step 3 	Step 6 

Figure 53: Refined Construction Process

10.6.11 Structural Exploration

In developing an expandable roof structure, a series of retractable systems and connections were explored as shown in Figure 54.

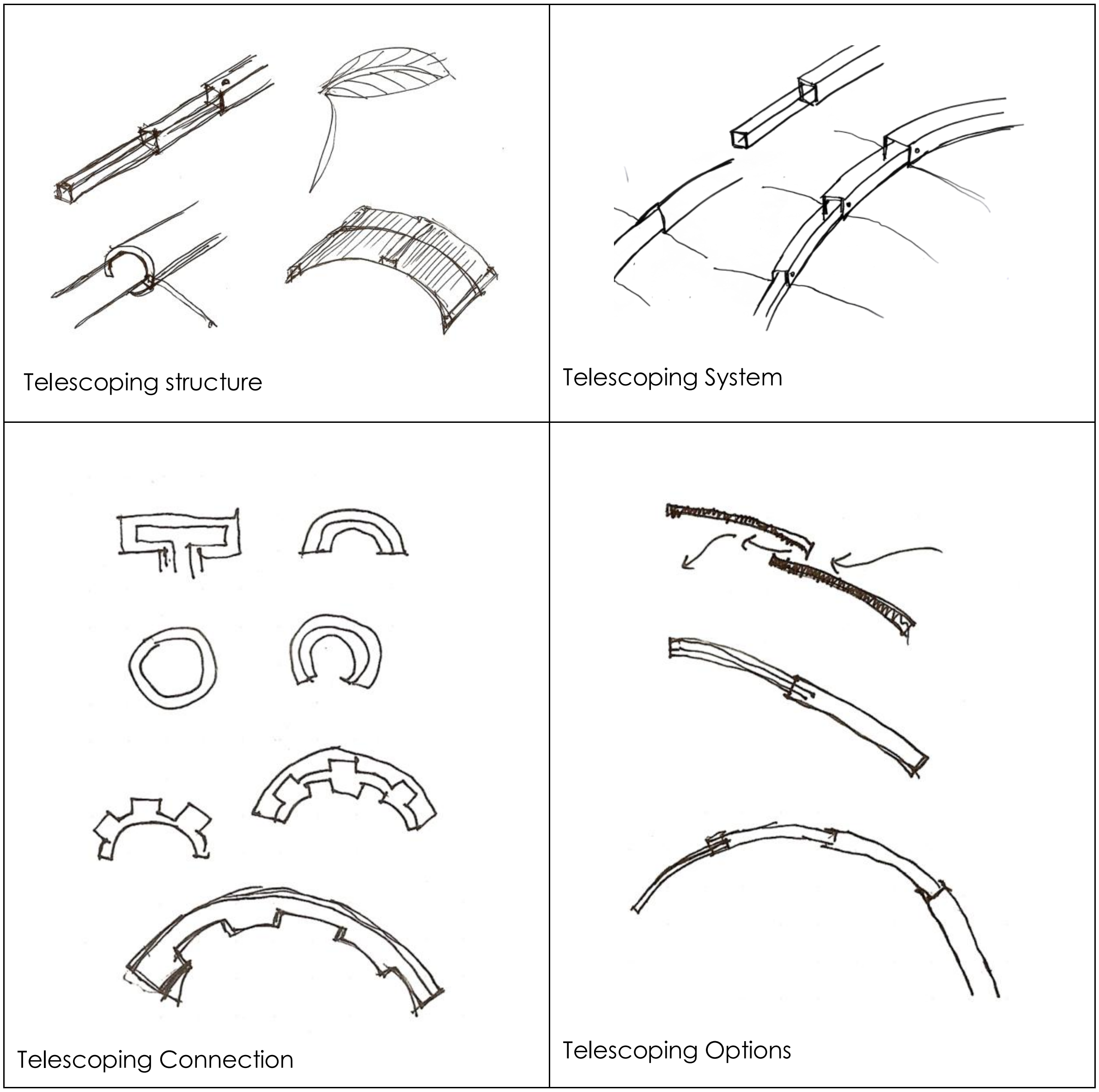


Figure 54: Structural Exploration Sketches

10.6.12 Roof Profile

The roof profile is inspired by the strong parallel ridge structure of a barrel cactus. Rather than having multiple ridges, the roof profile was initially inspired by a leaf structure with a thick central ridge supporting most of the weight followed by side ridges securing the roof form. However, as the roof system developed, the ridge profile was simplified. Figure 55 illustrates the different roof profile explorations.

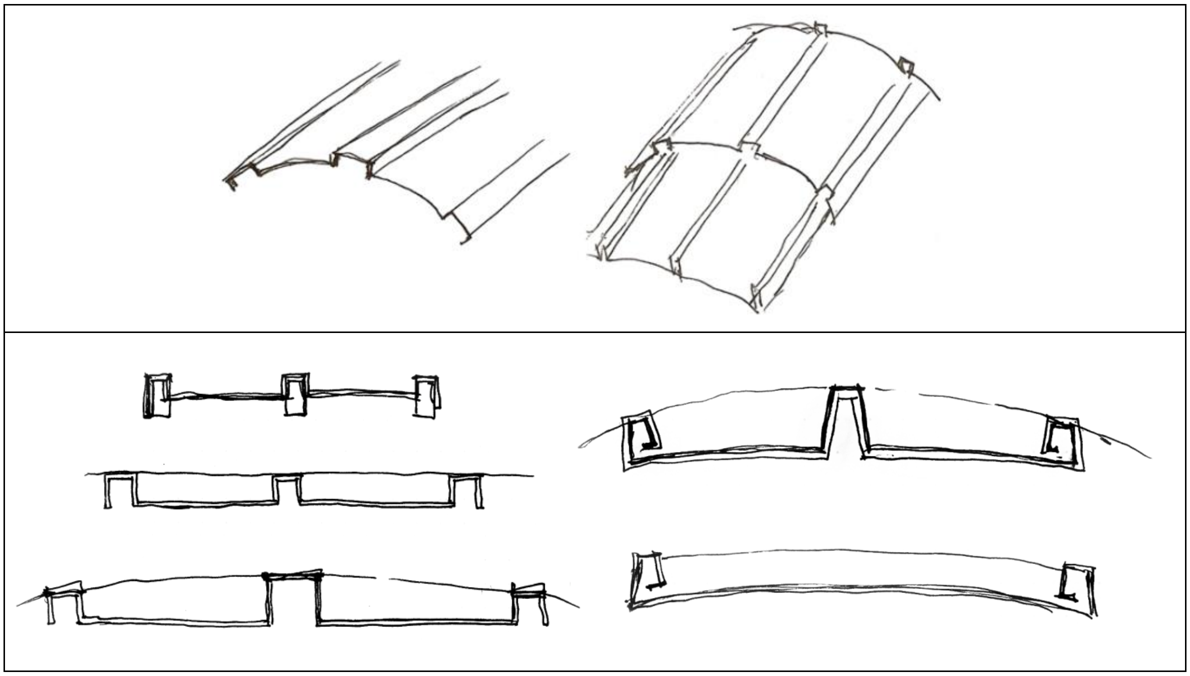


Figure 55: Ridge Profile Exploration

11.6.13 Details Exploration

Following the ridge exploration was the challenge of resolving the connections for the panels. Initially, the panels were based on a telescoping idea in which the structure of the panels gets smaller as it expands outward. As a result, the ridge of the profile had to be very simple in form. The search for a telescoping system led to the inspiration of a painter's ladder, where multiple ladders are locked in place and slide upward for expansion. Through this innovative and effective system, the panels can now be modular, and the connecting detail is much simpler.

The process of adding yet another layer of detail to the design led to the creation of a perforated roof catchment system that collects water while letting natural light into the interior space. Figure 56 is a detail sketch of the perforated roof detail and Figure 57 illustrates a three-dimensional model of the perforated roof detail. This exploration was later simplified due to the low annual rainfall found in most desert biomes. The incorporation of a catchment system in design is determined by two key factors: the amount of annual rainfall and the total collection surface area.

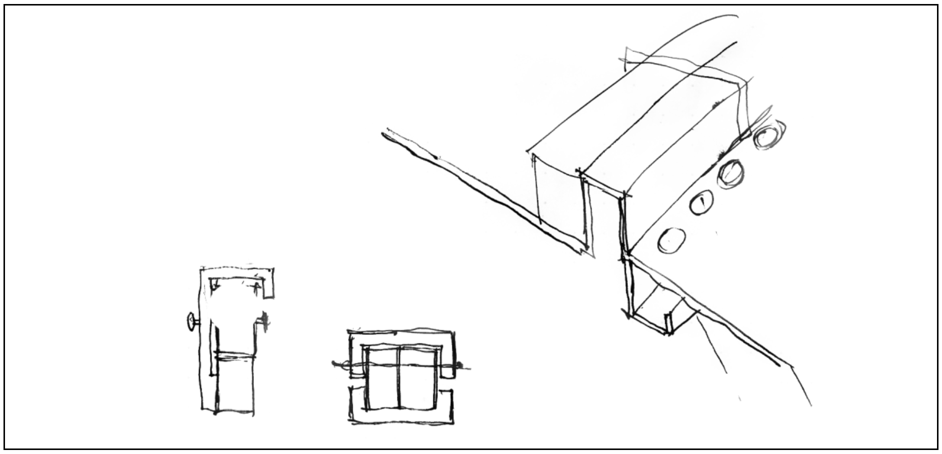


Figure 56: Detail Sketch

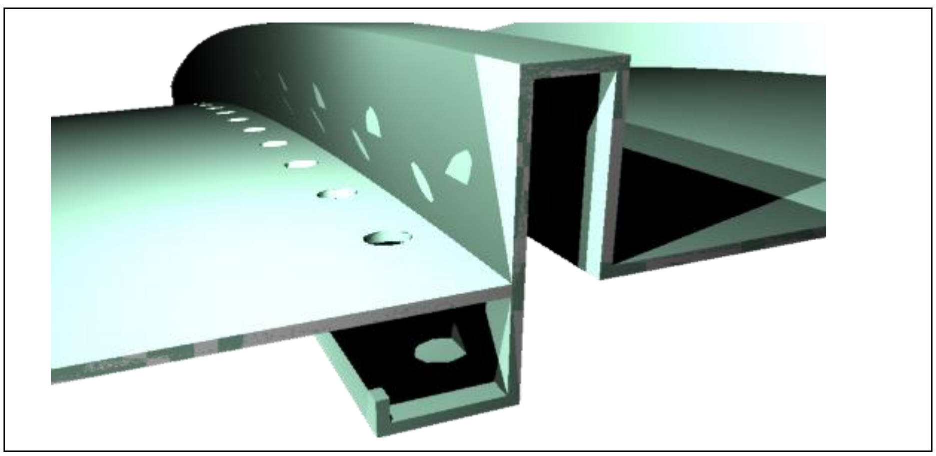
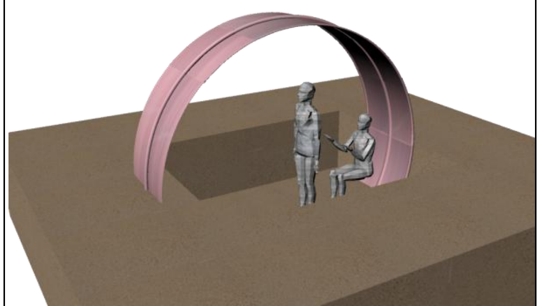


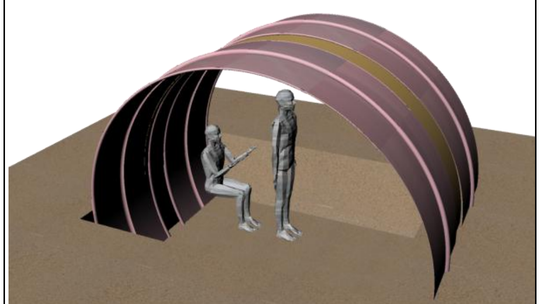
Figure 57: Detail section of perforated roof and catchment system

10.6.14 Growth and Expansion

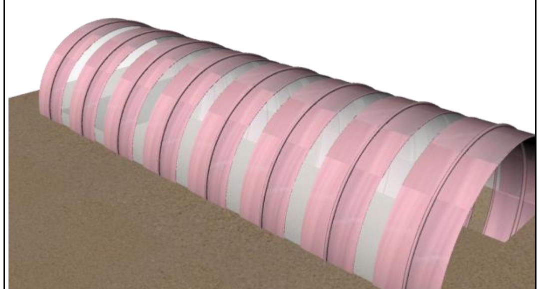
Although the design model is based on a two-person shelter, the possibility for the model to expand into larger units is considered. Given that the design is based on a modularized panel system, there are infinite solutions to how the panels can be configured to form greater units. Figure 58 illustrates some initial ideas of how the panels can be paired and grouped to form different size shelters based on the number of personnel.



Buddy



Squad

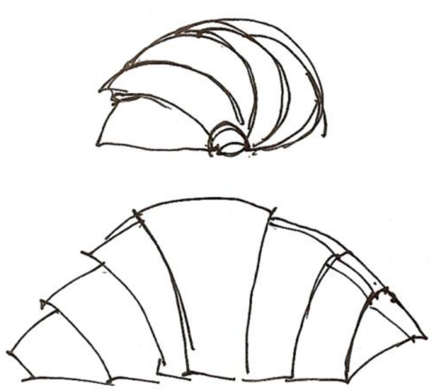


Company

Figure 58: Initial Expanding Idea

10.6.15 Armadillo Concept

In the process of searching for a retractable system, the canopy was also inspired by an armadillo's retracting shell system used for protection. The canopy could potentially act like a shell system that can expand and retract like the armadillo's shell. Figure 59 illustrates the process of how the expanding and retracting concept can apply to the process of construction.



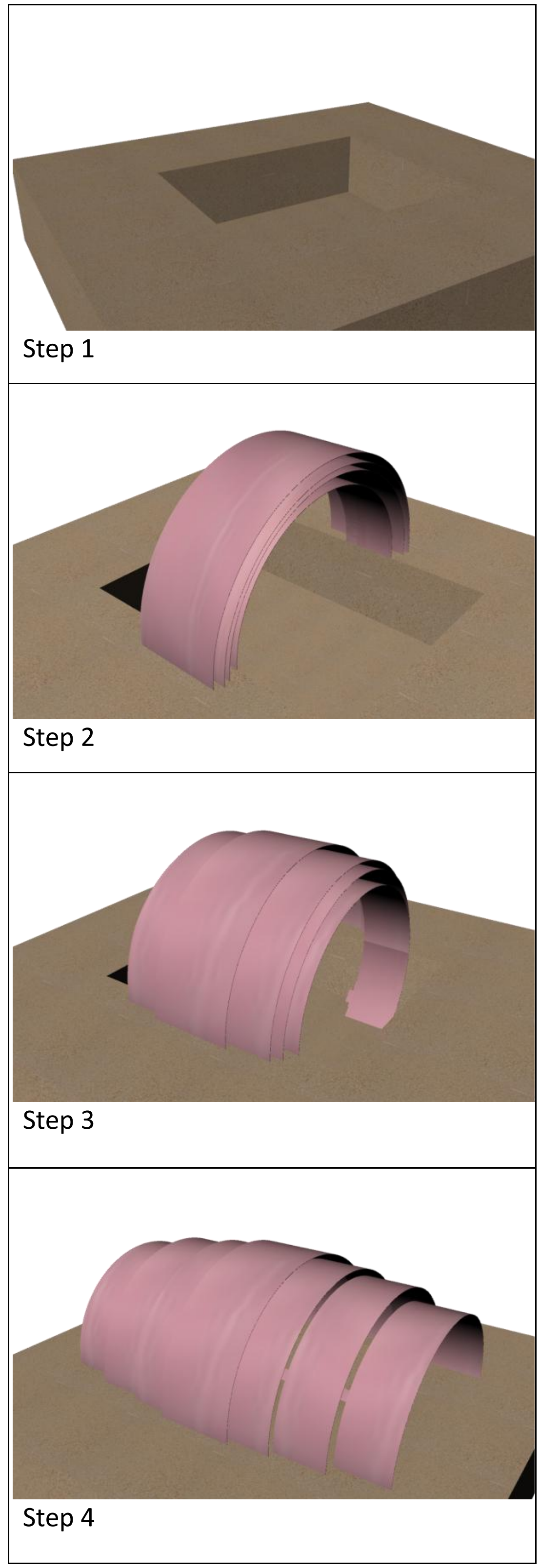


Figure 59: Armadillo Concept

10.6.16 Modularity

Modularity in architecture refers to the construction of an object by joining together standardized units to form larger compositions. Considering that war shelters are intended for use in a deployable contingency environment, modularity offers important design parameters for the project. Thousands of soldiers are often deployed to the same location over an extended period time, thus the mobility of equipment is critical. Size and weight are two main components that define the difficulty of the movement of equipment. How the design is fabricated, put together, and transported must be carefully thought out. Figure 60 illustrates the process of how the panels expand to become the roof and wall of the war shelter.

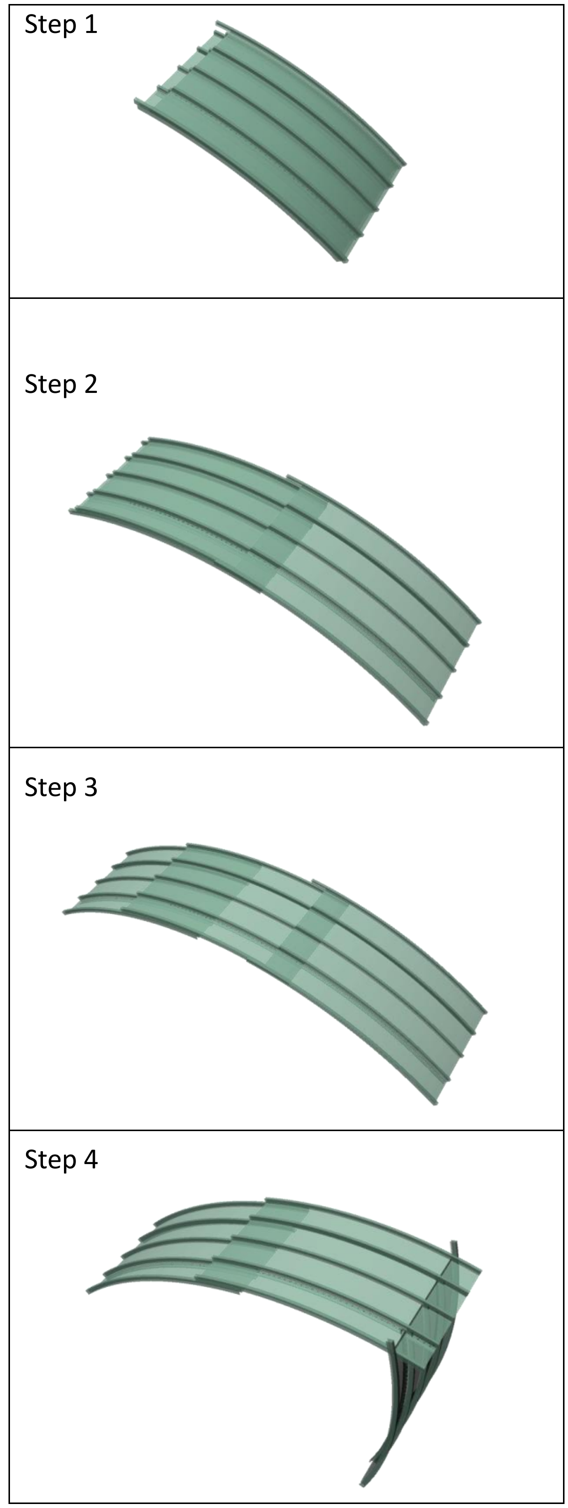


Figure 60: Modular Panel System

10.6.17 Multiple Configurations

The design model is based on a two-person shelter. However, the system is designed so that the panels are modular and expandable. Multiple panels can be grouped together to form different configurations for different functional spaces. Figure 61 illustrates some of the potential configurations using the same panel.

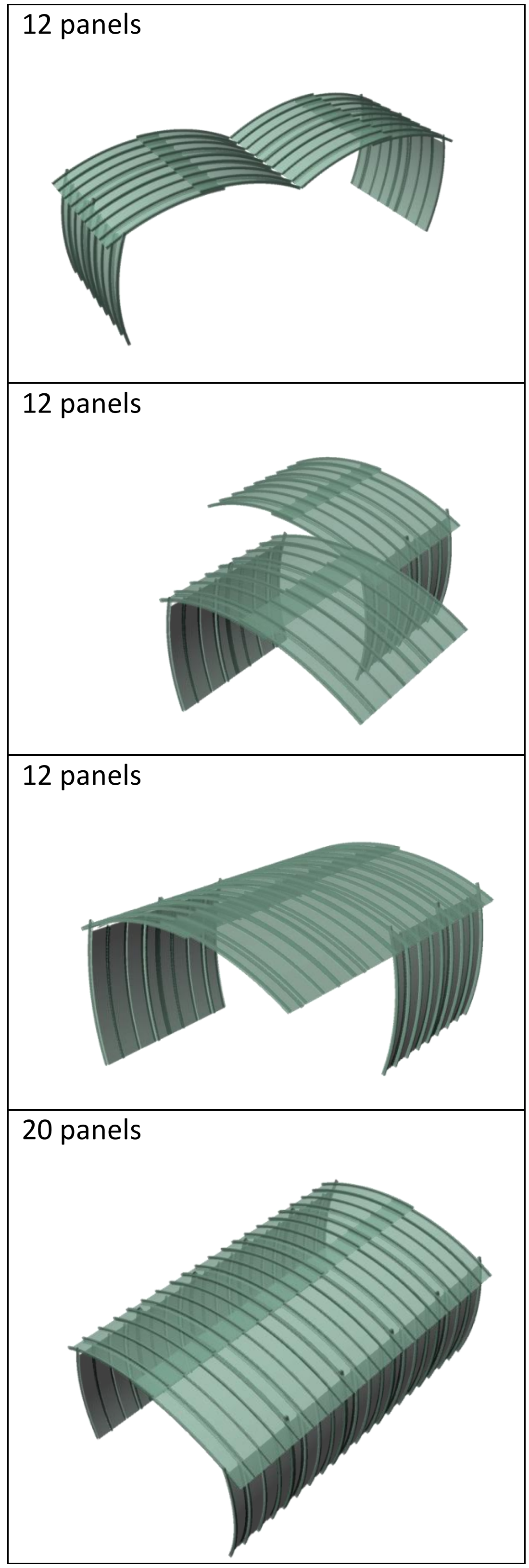


Figure 61: Panel Configurations

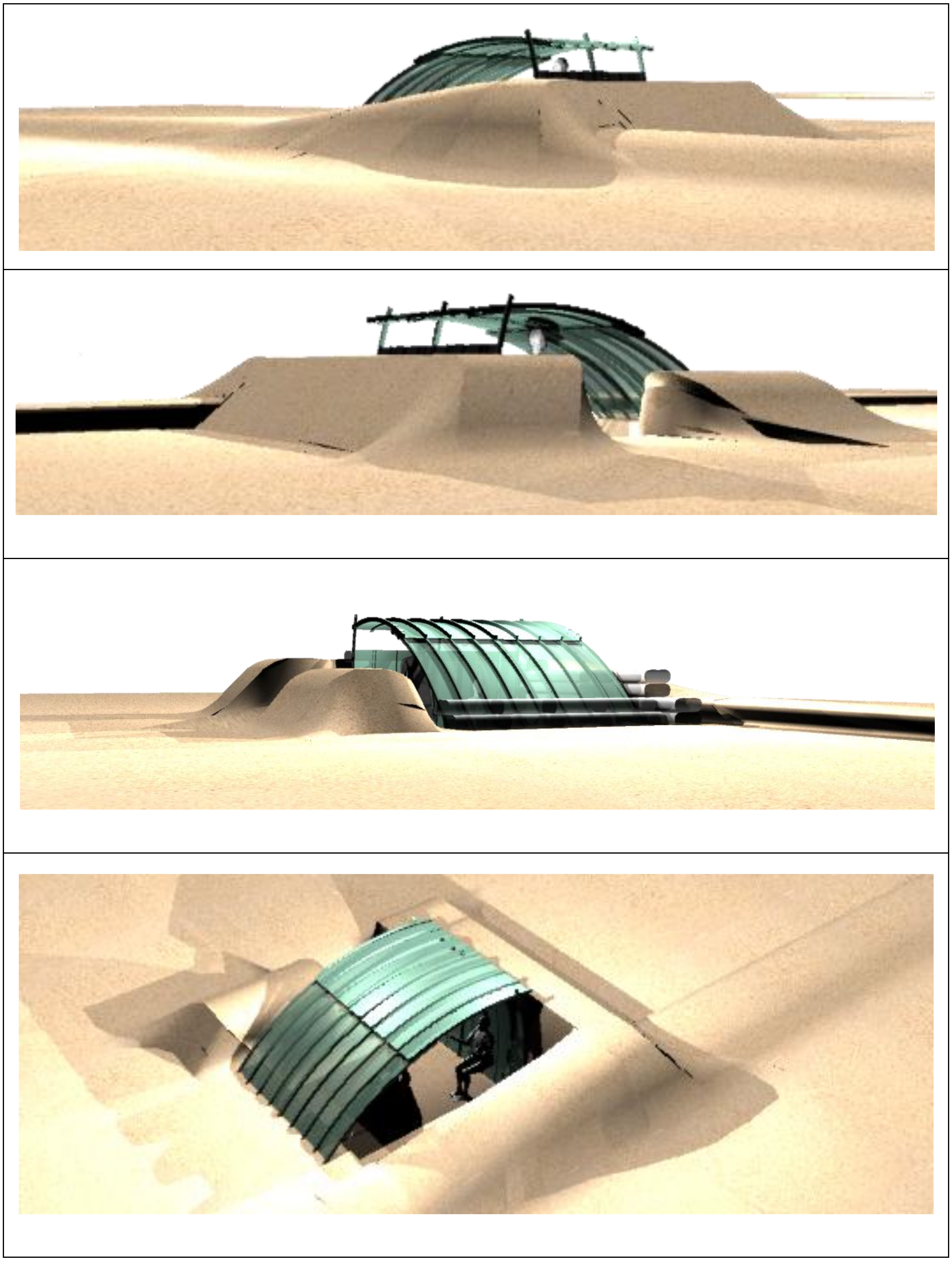
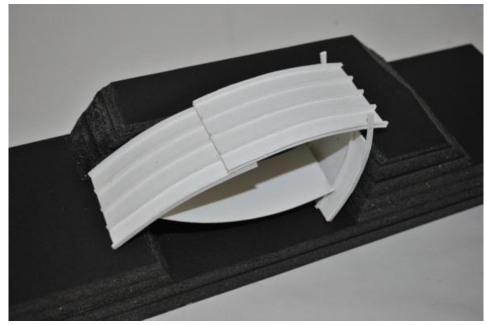


Figure 62: Initial Renderings

10.6.18 Section Model Study

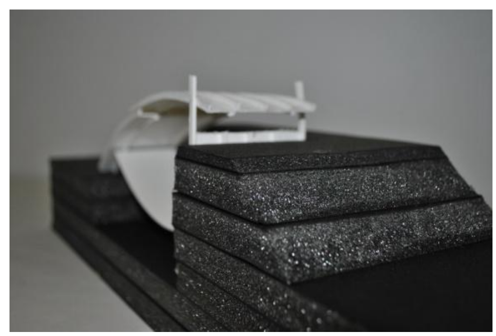
A section model was created at the scale of ½ inch to 1 foot to understand the construction process and to evaluate the spatial quality of the model. Initially, the design was based on a collapsible and retractable system, in which all of the panels were the same and stacked on top of each other. In the process of constructing the section model, one of the challenges realized was that in order to have a retractable and foldable system, the panels cannot all be the same. The wall panels might also need to be altered slightly in order to allow some natural ventilation into the space. Another issue that came up was the strength of the ridges that support the entire roof structure. The hinge of the connection has to be really strong, and without a bracing system across the ridge, the entire roof might be lifted by strong winds. Figure 63 captures various views of the section model.

Aerial View



View of Living Space

View from Front Line



View of Roof from Berm

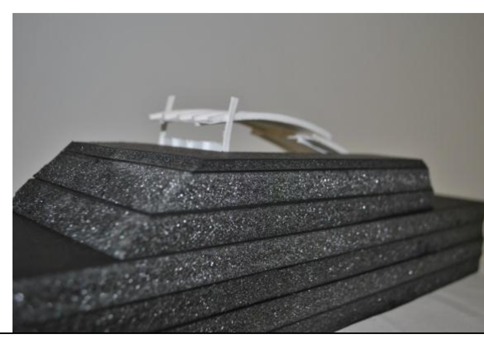


Figure 63: Views of Section Model

10.6.18 Living Attributes

Part of the process of creating a comfortable space is by providing the basic living necessities such as a sleeping area and a storage space. To maximize the potential usage of the panels, multiple design options were explored. Figure 64 illustrates the idea of how a sleeping cot can potentially hook onto the panels so that the cot can be elevated off ground. When not in use, the cot can be folded up to become the seat or back rest of a chair.

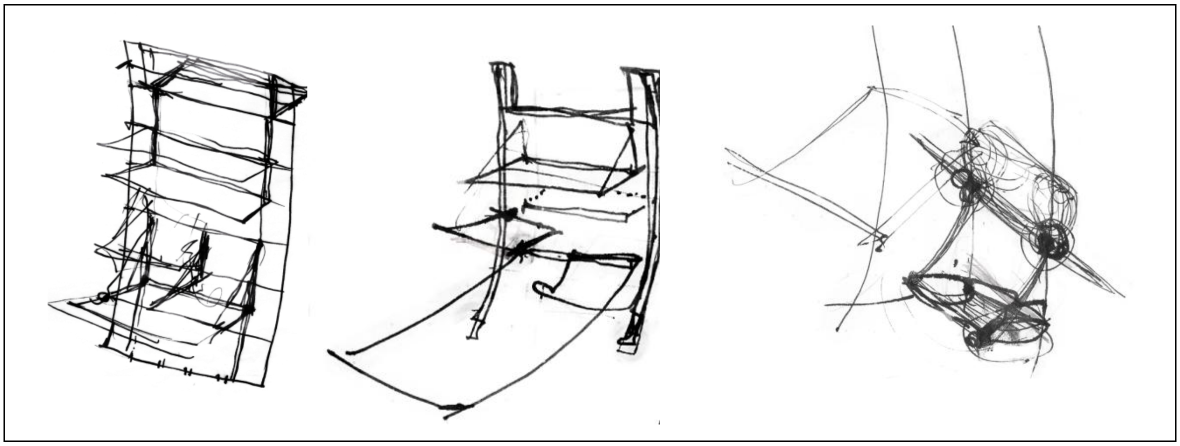


Figure 64: Cot Design Sketches

The design must also provide storage space for essential equipment. The three items that a soldier must have readily assessable are a weapon, Kevlar (helmet), and body armor. Provided that a peg or stake system is used to anchor the panels, the same peg can be used as a hanger system for the storage of equipment (Figure 65). Figure 66 is a perspective view of the stake and hanger system.

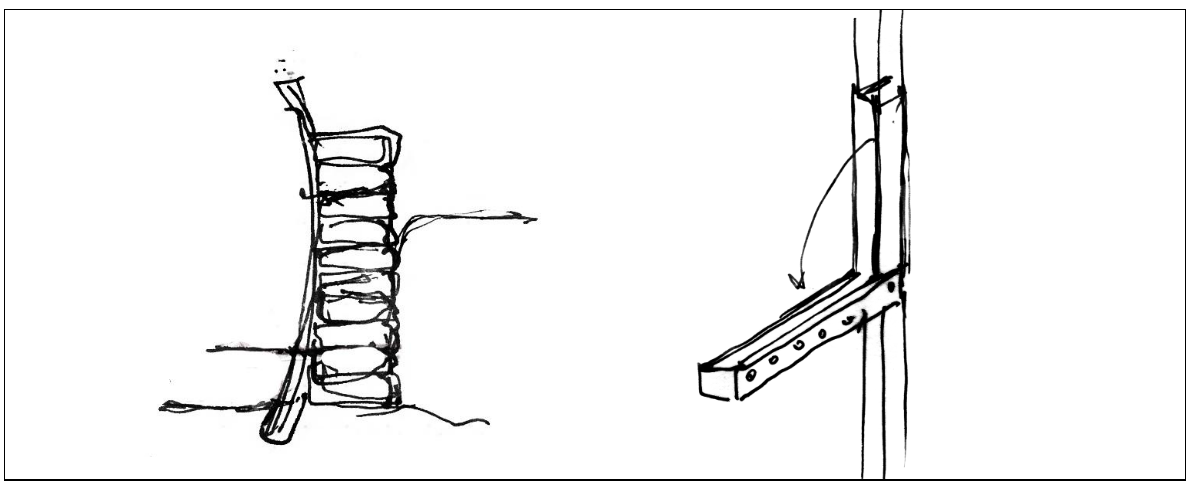


Figure 65: Peg System

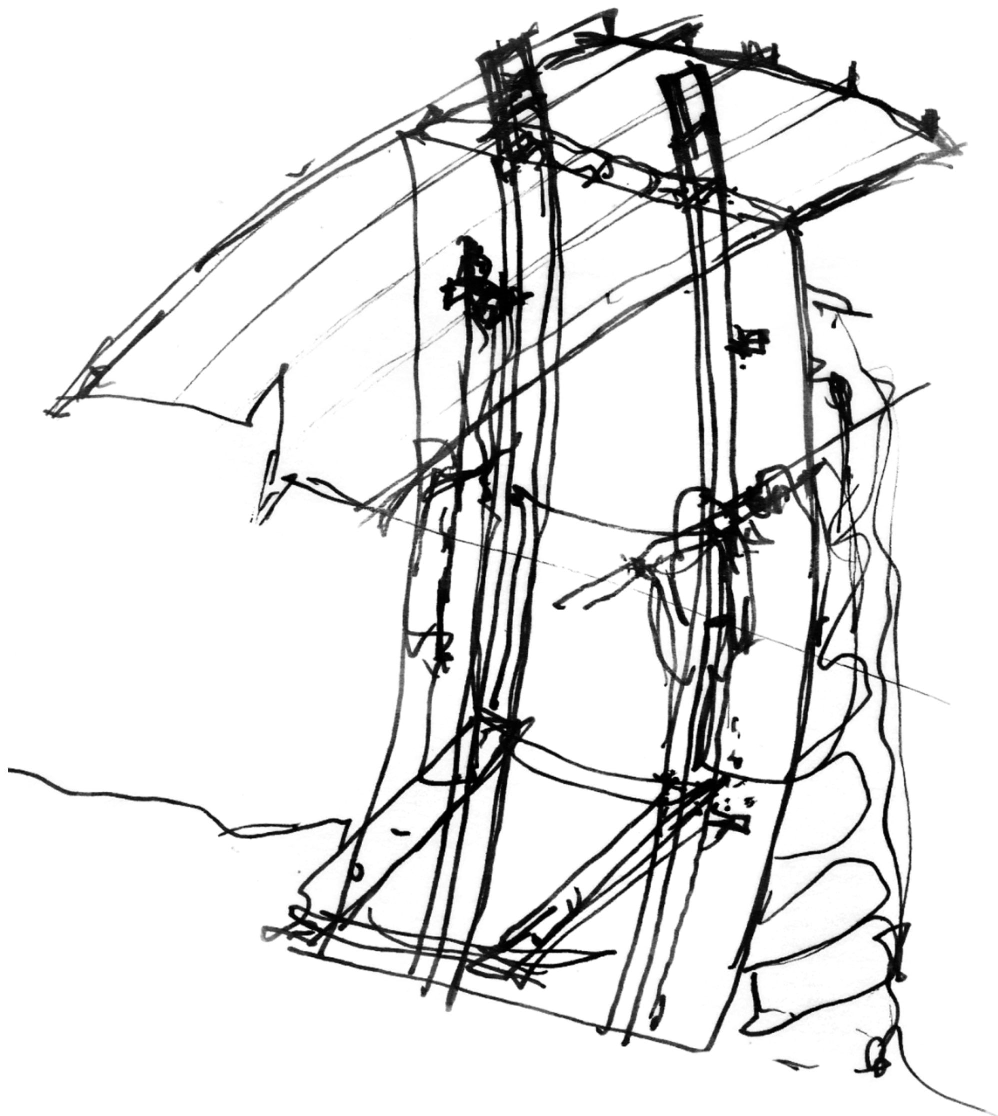


Figure 66: Perspective sketch of the stake and hanger system

10.7 Design Example

The final model was the result of many inspirations found in nature. One idea led to the next. The study of animals and plants in the desert led to the extraction of nine biomimetic principles that inspired the design of the project. A collective study of burrows and canopy designs, along with the consideration of various military requirements, resulted in a war shelter model that addresses comfort, protection, modularity, materials, and greenhouse gas emissions. Figure 67 is an exploded diagram that clearly identifies each of the design components follow by a list of key characteristics of the model.

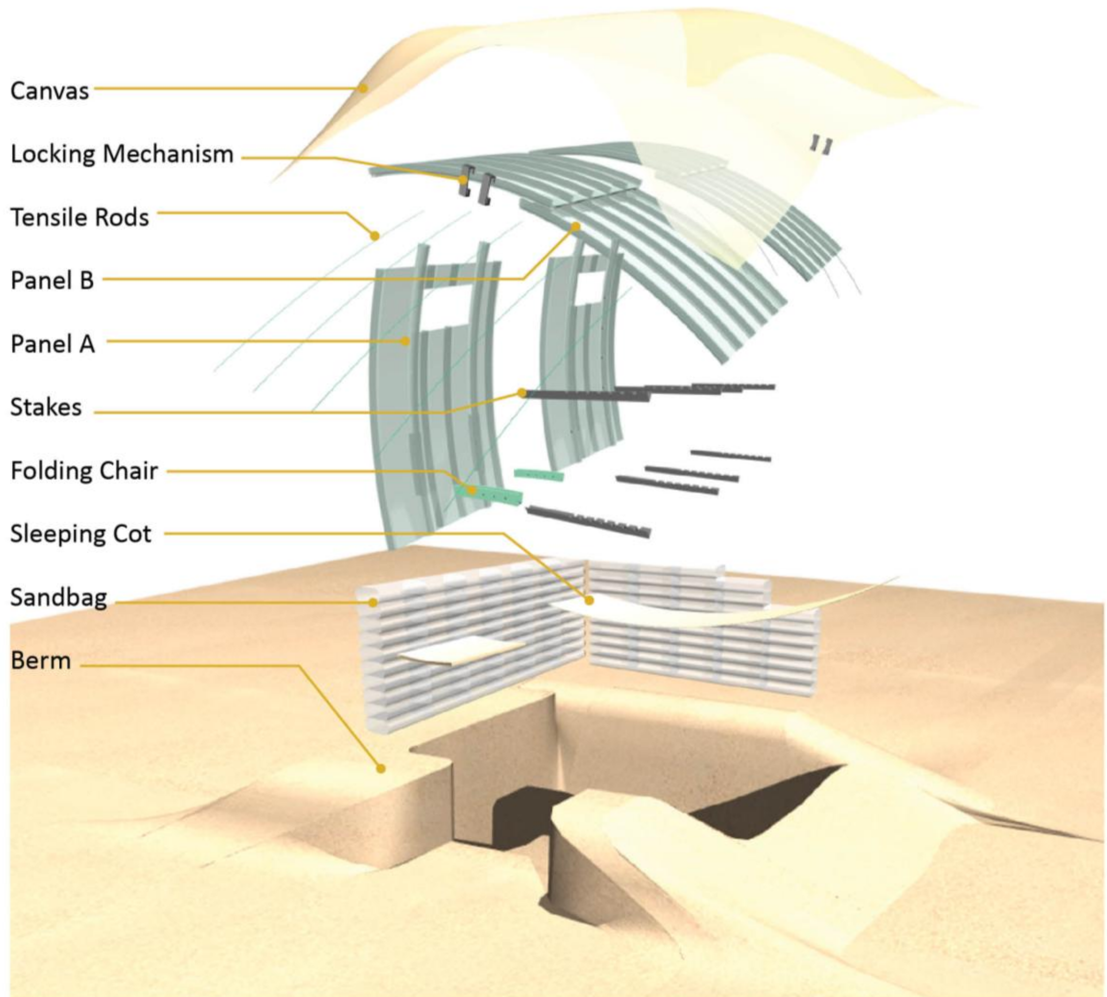


Figure 67: Exploded Diagram of Design Model

The key characteristics of the design model include:

- Burrowing- utilizing the depth of soil to reduce surface temperature
- Berming- maximizing the use of site materials to provide protection and shading
- Parallel Ridge Roof Profile- minimizing the amount of solar radiation on the roof and reducing heat gain
- Thicker Envelope- reducing the transfer of heat while offering greater protection
- Double insulated roof- reducing the heat flow from one layer to another
- Greenish gray roof color- minimizing the amount of solar radiation while offering protection
- Low profile- providing a low arch profile that blends in with the undulating sand dune
- Modular Panel-improve portability and transportability

10.8 Final Drawings + Renderings +Model

- Drawings (See Appendix G)
- Physical Model (See Appendix H)
- Renderings (See Appendix I)

11. SIMULATION AND ANALYSIS

The purpose of the simulation and analysis was to test and compare the design model against two existing war shelter models: a small modular general purpose tent system and an air-conditioned, containerized housing unit. One of the most widely utilized design analysis software tools used today by both professionals and students is the Autodesk Ecotect Analysis tool. Autodesk Ecotect Analysis-sustainable analysis software is a comprehensive design tool that offers a wide range of simulations and building energy analysis functionality that can improve the performance of existing buildings and new building designs. Autodesk Ecotect Analysis enables one to simulate a building's performance within the context of its environment. Each model was run through the Ecotect Analysis tool for simple simulations and calculations regarding thermal performance, solar radiation, and computational fluid dynamics (CFD), otherwise known as the study of air movement. The calculations provide a set of data to evaluate the levels of comfort within each model. The goal is to demonstrate that a biomimetic design model is capable of improving the level of comfort within a space.

11.1 Site Selection

In order to do a proper analysis in Ecotect, a specific site and location along with a proper set of weather data must be identified. Though it would be ideal to use Iraq, the place that inspired the project, as the location for the simulation, a correct set of weather data from Iraq could not be identified. Therefore, the simulation was based on Kuwait, a country south of Iraq with similar climatic conditions. (Figure 68)

Figure 68: Map of Kuwait

11.1.1 Kuwait Climate

Situated in one of the driest, least-hospitable deserts on earth, Kuwait's climatic conditions are generally hot and arid, with scant rainfall. During the dry season, between April and September, the heat is severe. Daily temperatures ordinarily reach 111°F (44°C), and at times the temperature can reach as high 130°F (54°C).[63] Figure 69 represents the average weekly temperature within a year. The prevailing wind direction is from the northwest as shown in Figure 70. Northwestern winds are hot and dry during the summer due to the long distance they travel over the deserts of Saudi Arabia, Syria, Jordan, and Iraq. Annual rainfall averages about 1 to 7 inches (20-180mm). However, the rainfall in Kuwait has no specific trend. The rainy days might exceed 40 days in some years, and the mean total rainfall rate can reach 336 mm. Rain affects patches in Kuwait rather than the whole country. Rain can start in November and continue intermittently until April. Sometimes, January is the rainiest month of the year. Figure 71 represents the yearly rainfall averages from 1996 to 2007. Figure 72 illustrates the monthly diurnal averages and daily conditions.[64]

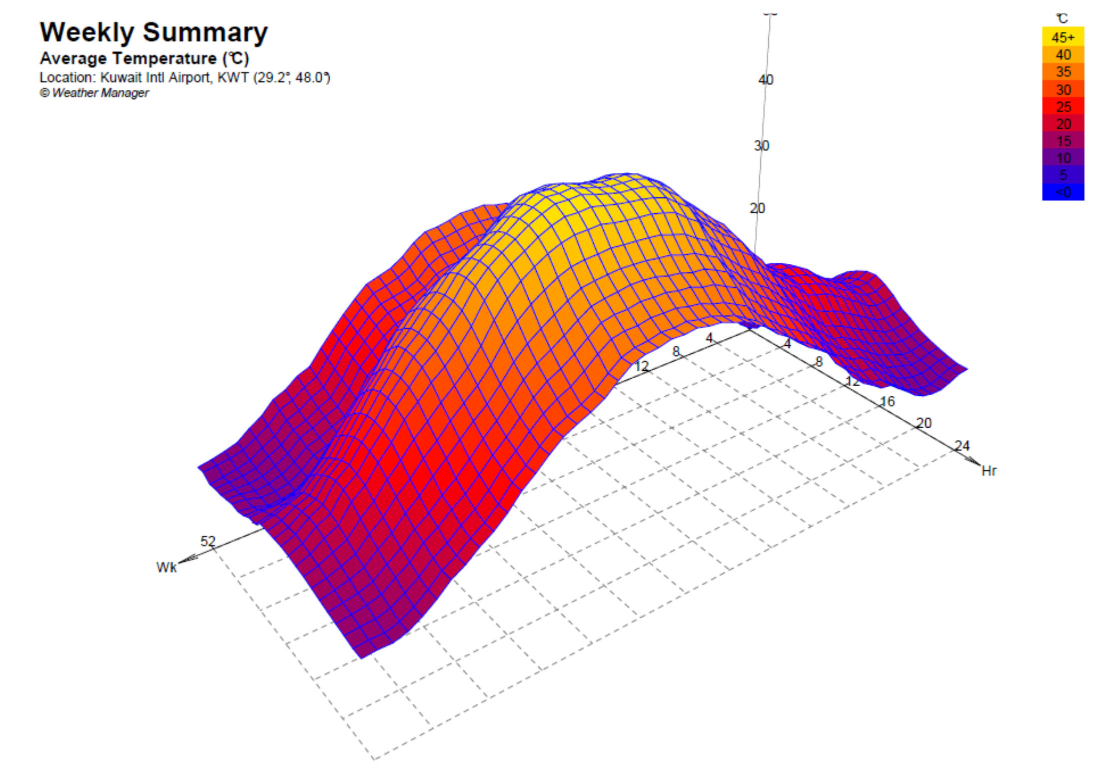


Figure 69: Average Air Temperature

[63] "Kuwait: Climate -- Britannica Online Encyclopedia." Encyclopedia - Britannica Online Encyclopedia. http://www.britannica.com/EBchecked/topic/325644/Kuwait/45144/Climate (accessed March 15, 2011).

[64] "Kuwait National Meteorological Network." Kuwait Institute for Scientific Research - KISR . http://www.kisr.edu.kw/default.aspx?pageid=503 (accessed March 4, 2011).

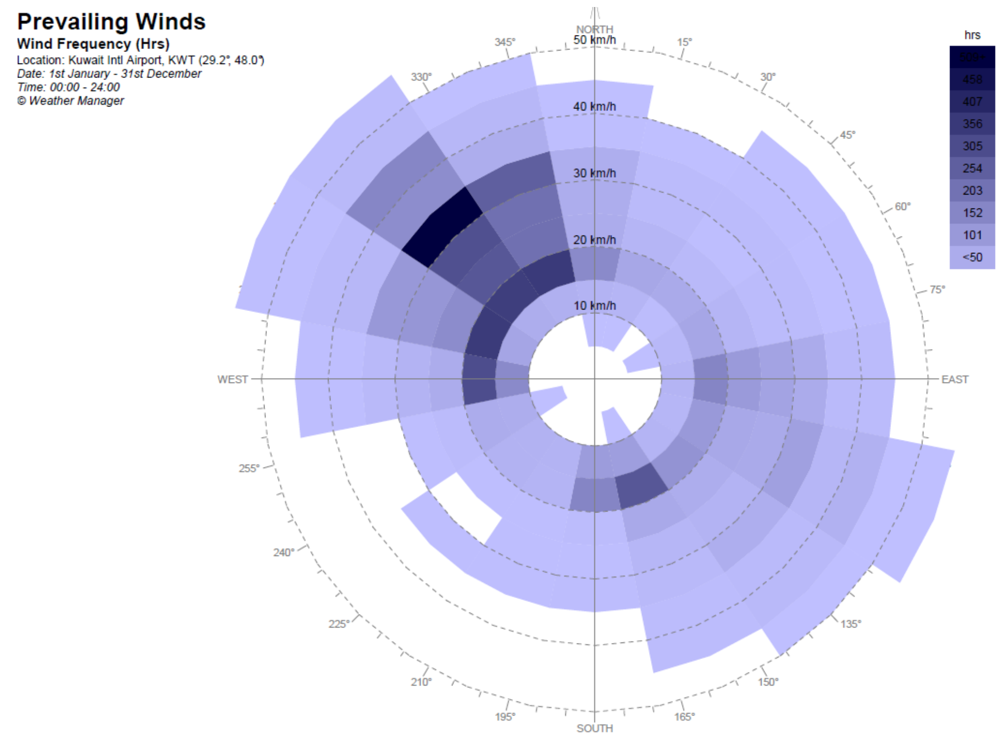


Figure 70: Wind Diagram

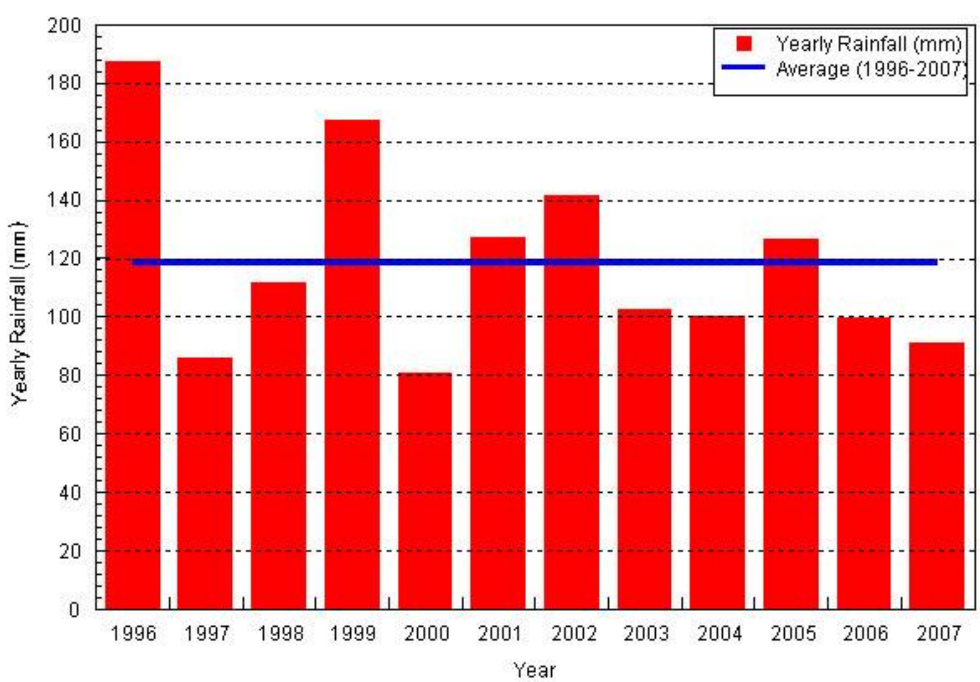


Figure 71: Yearly rainfall from 1996 to 2007 in Kuwait

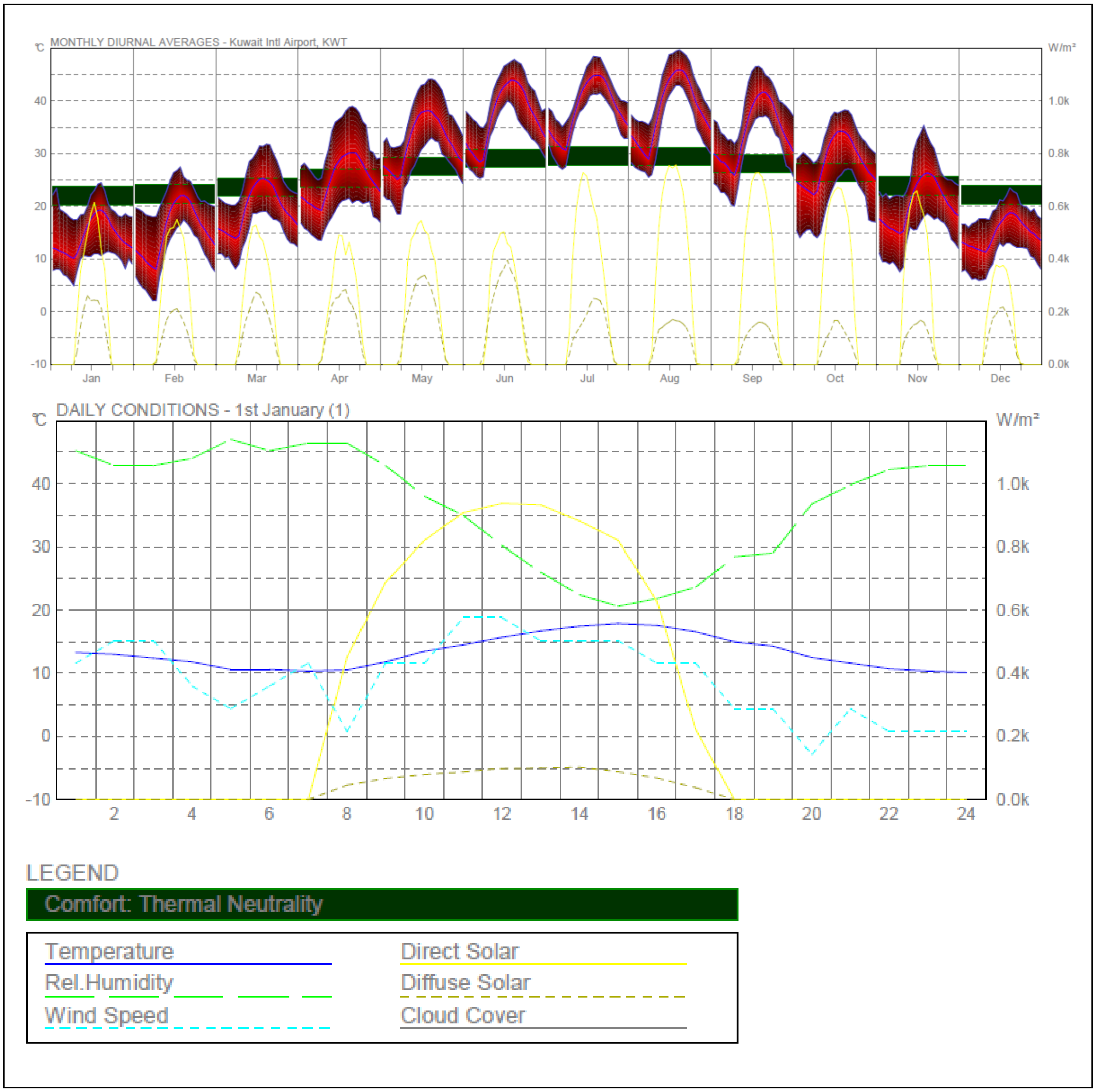


Figure 72: Monthy Diural Averages and Daily Conditions

11.2 Material Selection

A specific material for the panel has not been identified, but based on the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2007 and the 2009 International Energy Conservation Code (IECC), an R-value of 30 is recommended. The ASHRAE Standard addresses building envelope and system requirements for commercial buildings, residential buildings higher than three stories, and semi-conditioned buildings. According to the latest version, the minimum required prescriptive R-value for roof and wall insulation levels is 20.[65] The 2009 IECC is a building code created by the International Code Council and adopted by many state and municipal governments in the United States for the establishment of minimum design and construction requirements for energy efficiency. Southeast Arizona is characterized by its hot and dry climate zone; the recommended ceiling R-value for that region is 30. Therefore, the recommended R-value for the roof and wall panels is 30. For the purpose of the simulation and analysis, this material will be identified as the super material.

Sand is a key material component of the design model and therefore, needs to be addressed in the modeling and simulation of the design model for proper analysis. The specific R-value for sand is hard to determine. In this case, sand is treated as rammed earth, which is typically used for adobe or sun-dried earth constructions. According to laboratory tests provided by ASHRAE, a 10 inch thick adobe wall with ¾ inch of stucco on the exterior and ½ inch of gypsum plaster on the interior has an R-value of 3.8.[66]

11.3 Models Comparison

The design model is designed to meet the requirements of an initial phase of construction in a contingency environment. Therefore, the design model is tested against two existing war shelters, a containerized housing unit (CHU) and a small modular general purpose tent (MGPTS), which are typically used during the initial and temporary phases of a contingency operation. The CHU is made up of mostly corrugated metal while the MGPTS is composed of primarily vinyl-coated polyester fabric, a common material for canvas. Both the CHU and the MGPTS were tested against its own specified material for thermal comfort and solar radiation.

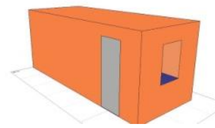
[65] "Climate Zones Map | Atlas Roofing Corporation." Isological Home Page | Atlas Roofing Corporation. http://www.isological.com/general.php?section_url=1-39 (accessed March 10, 2011).

[66] McHenry, Paul Graham, AIAJohn Wiley & Sons, Inc., and New YorkUnited Stateshttp://bookstore.greenbuilder.com/index2.books?rid=49. "Earth Materials." Earth Materials. http://earth.sustainablesources.com/ (accessed March 2, 2011).

Aside from testing with its own specified R-value material, the design model was also tested with the two specified materials used by the CHU and the MGPTS for comparison. Table 10 outlines the specification of each model's dimension, weight, and material composition.

Material Composition

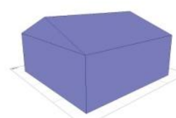
CONTAINERIZED HOUSING UNIT (CHU) SPECIFICIATION



DIMENSION AND WEIGHT	
Length	20'
Width	8'
Height	9'6"
Floor Area	160 sq. ft
Window	

MATERIAL COMPOSITION		
Material	**Thickness**	**R Value (ft²·°F·h/Btu)**
Ceiling (Corrugated)	2.5"	12.5
Wall (Corrugated)	2.5"	7.9
Floor (Corrugated)	4.7"	12.5

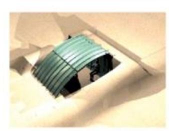
MODULAR GENERAL PURPOSE TENT SYSTEM (SMALL)

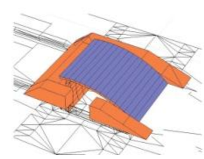


DIMENSION AND WEIGHT	
Length	18'
Width	18'
Height	11'5"
Eave Height	7'
Floor Area	324 sq. ft.

MATERIAL COMPOSITION		
Material	**Thickness**	**R Value (ft²·°F·h/Btu)**
Fabric w/Air (3.5")	4.2"	12.6
Fabric	0.7"	6.8

DESIGN MODEL





DIMENSION AND WEIGHT	
Length	11'
Width	10'
Height	7'
Floor Area	110 sq. ft

MATERIAL COMPOSITION		
Material	**Thickness**	**R Value (ft²·°F·h/Btu)**
Super Material	3"	30
Corrugated Metal	2.5"	12.5
Canvas	.7"	6.8
Rammed Earth	2-3'	8.5-12.5

Table 10: Material Composition

11.3 Thermal Analysis

There are many ways to measure comfort using the Ecotect Analysis tool. Below is a list of methods used to measure thermal comfort within a closed space followed by detailed descriptions.

How to measure comfort?

- Monthly Comfort Time

  -Displays the amount of percentage of time each month that the temperature in each zone is considered comfortable.
- Spatial Comfort Analysis

  -Calculates the distribution of comfort parameters over the analysis grid, if it is currently visible in the model. Once calculated, these values will interactively update as you change the date and time.
- Degree Hours

  -Sums the number of degrees above or below the comfort band that the internal zone temperature is for each hour of each month. This indicates the level of comfort, not just the time.
- Percentage of Time

  -Calculates the proportion of time each month that the internal zone temperatures were outside the comfort band.
- Total Hours:

  -Calculate the proportion of time each month that the internal zone temperatures were outside the comfort band.

11.3.1 What is an R-Value?

An R-value is a measure of the insulation's ability to resist heat traveling through it. The higher the R-value, the better the thermal performance of the type of insulation. The R-value depends on the insulation's material, thickness, and density. The effectiveness of the insulation's resistance to heat flow also depends on how and where the insulation is installed. For example, insulation that is compressed will not provide its full rated R-value. In addition, the overall R-value of a wall or a ceiling will be different than the insulation alone because some heat flows around the insulation through the studs and joists. Finally, the amount of insulation or R-value is also dependent on the climate, type of heating and cooling system, and location of the insulation.[67]

11.3.2 Thermal Analysis Methodology

The main purpose of the thermal analysis is to evaluate the effectiveness of burrowing and berming in improving the comfort level within a space. The design model is tested against two existing war shelters: a small modular general purpose tent and an un-air-conditioned, containerized housing unit. To ensure that the calculations are valid for the comparison, several assumptions have been made.

In order to conduct a thermal analysis in Ecotect, the materials of each model must be identified. Since a material has not been selected for the design model, a list of materials will be tested for comparison. The design model will be tested with the existing models' materials, a popular new building insulating material known as aerogel, and a hypothetical material based on a suggested R-value by the ASHRAE Standard 90.1-2007 and the 2009 IECC.

Within the Ecotect Analysis tool, there are many factors that can affect the results of the calculations. In order to come up with analysis that is convincing, a set of control data was put together. Based on the materials of each model, only the thickness and R-value will be assigned for the calculations. Table 10 provides the dimensions, weight, and material composition of each model. Finally for consistency in calculation and comparison, the two existing models will not be air conditioned because the design model is intended to be naturally ventilated.

11.3.3 Thermal Analysis Assessment

Based on the various thermal analyses conducted in Ecotect, the design model indicates signs of thermal comfort improvement throughout the year in comparison to the CHU and MGPTS (tent). Meanwhile, the change of material within the design model did not make much of a difference. Although there was a thermal difference between each of model analyzed, the data collected were not adequate enough to make a coherent conclusion. There are many factors that can alter the results of the calculations. The design model for instance is not a fully enclosed space and therefore cannot perform a true thermal analysis. Material specification needs to be broken down further. The size and number of occupants per structure also varies and will affect the calculations. Refer to Appendix H for details of the thermal analysis results.

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[67] "Energy Savers: The R-Value of Insulation." EERE: Energy Savers Home Page. http://www.energysavers.gov/your_home/insulation_airsealing/index.cfm/mytopic=11340 (accessed March 1, 2011).

11.4 Solar Radiation Analysis

Autodesk Ecotect makes it possible to analyze solar radiation in detail. With Ecotect, one can calculate solar exposure for building envelopes and compute solar radiation analysis values. The purpose of the solar radiation analysis is to test the effectiveness of a double layer roof based on the biomimetic idea of in-between space.

11.4.1 Solar Radiation Methodology

In order to do a true thermal analysis, the entire model must be an enclosed space. Since the sides of the model are open, the thermal calculation might not be accurate. Therefore, a solar radiation analysis is conducted to prove whether or not a double layer roof system will reduce the amount of heat gain inside. The method is to simply map and measure the incident solar radiation that falls upon each of the surfaces. The goal is to test whether two surfaces will reduce solar radiation and minimize the heat build-up within a building.

11.4.2 Solar Radiation Assessment

Based on the biomimetic design principle of an in-between space, hypothetically, the amount of heat gain will reduce with an additional layer of coverage. Though the solar radiation analyses in Ecotect indicated reduction in heat gain, the data collected alone are not sufficient to make a justifiable conclusion. Further research in materials and alternative methods of solar radiation calculation need to be explore. Refer to Appendix I for details of the solar radiation calculations performed in Ecotect.

11.5 CFD Air Flow Analysis

The exact patterns of airflow occurring in and around a building and the distribution of heat can be modeled using Computational Fluid Dynamics (CFD). CFD airflow analysis can be done on a building's external and internal aerodynamic characteristics. In the case of this project, an internal CFD simulation is analyzed. Internal CFD simulations can be used to assess the impact of system design and spatial layout on indoor quality and thermal comfort. The purpose of this simulation is to demonstrate that there is air movement within the space based on the design model and air conditioning is not necessary.

11.5.1 CFD Air Flow Analysis Methodology

A CFD air flow analysis requires the use of two programs, Ectotect and WinAir. First, the analysis grid must be set up correctly in Ecotect to perform the CFD cell blockages calculation.

The calculations will then be imported to WinAir to calculate the CFD data. Lastly, the CFD data will be loaded back into Ecotect to complete the CFD Analysis, which provides the air flow rate for the design model. The wind setting is based on Kuwait's prevailing direction from the Northwest at a speed of 30 km/h.

11.5.2 CFD Analysis Assessment

The CFD analysis illustrates that if the model is oriented towards the prevailing wind, there is greater air movement within the space. Figure 73 shows a three-dimensional view of the rate of airflow happening around and inside the model. Refer to the legend for specific data on the rate of the airflow in m/s. Refer to Appendix J for details sections of the CFD calculations performed in Ecotect.

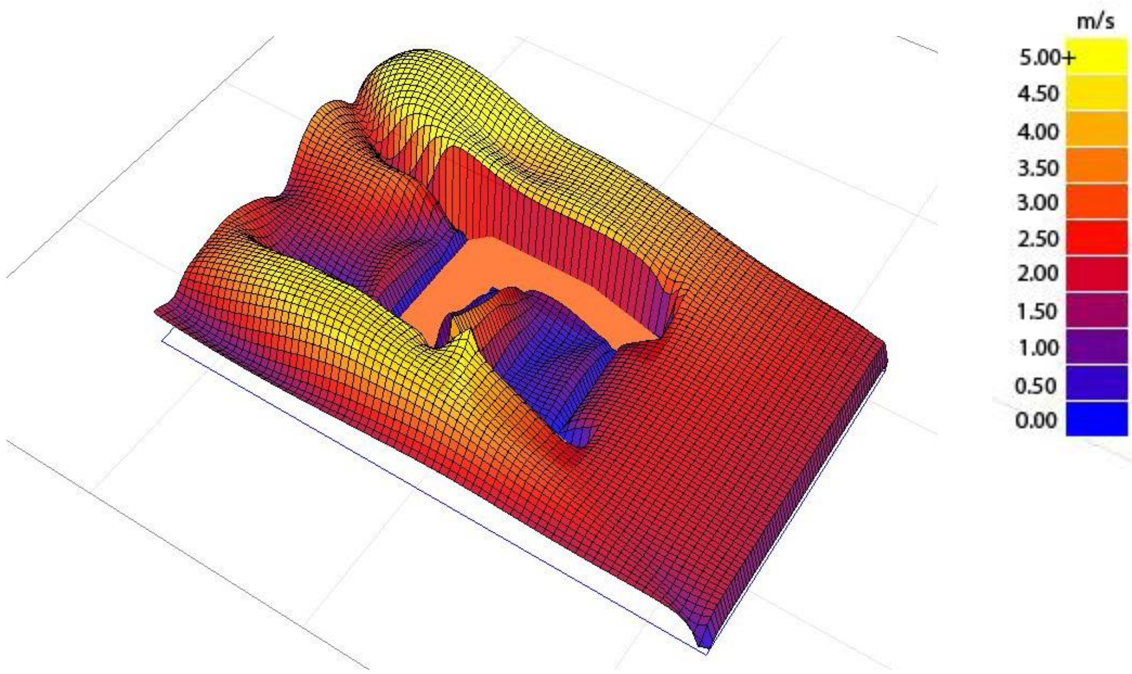
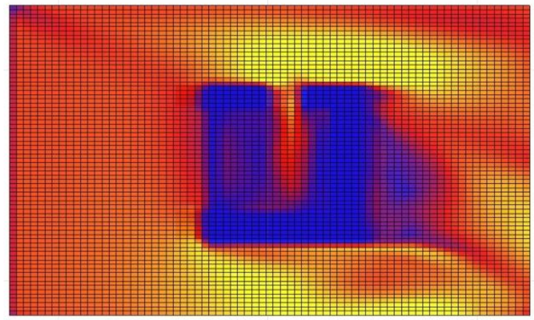


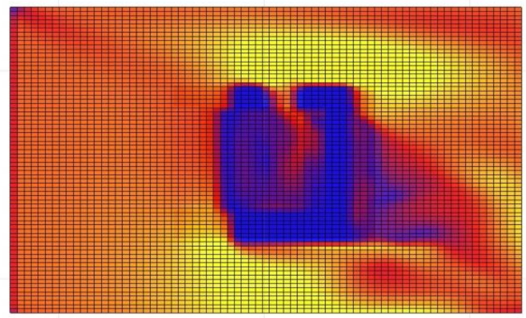
Figure 73: 3-D Air Flow around the Design Model

11.5.3 Air Flow Rate

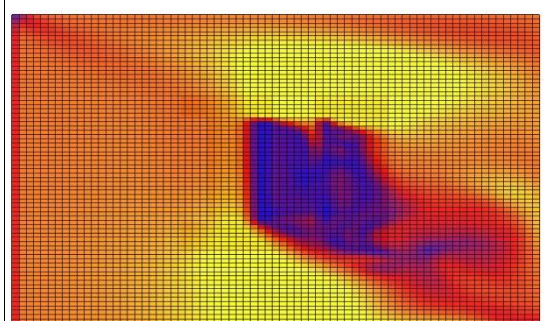
Figure 74 represents the rate of airflow around the design model taken at 1 foot increments from the ground. Based on the legend to the far right, blue represents no air movement and yellow represents 5 m/s. At 0 feet, the strongest sign of air movement comes from the entry. The large amount of blue is the result of the berming around the interior space. At 1 foot, air movement in the interior space results directly from the entry point. At 2 feet from the ground level, air movement is happening around the space. At 3 feet, air movement is evident in the direction of the window open to the west. At 4 feet, air circulates the entire space. This analysis resulted in several design suggestions. One is the height of the berm, which should be lower toward the direction of the prevailing wind. Two is that an opening in the lower panel might increase the air circulation inside the space.



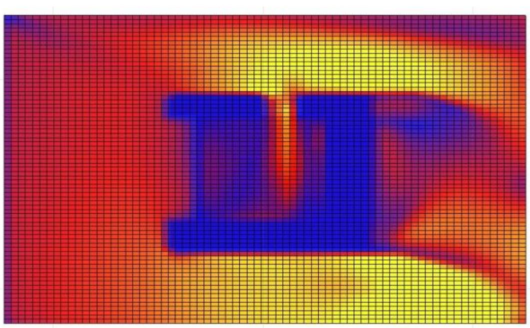
1 Feet



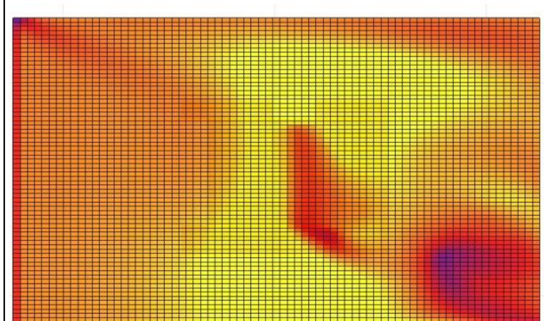
2 Feet



3 Feet



0 Feet



4 Feet

Figure 74: Air Flow Rate by Section

11.6 Comparative Analysis

11.6.1 Frame of Reference

The purpose of the analysis is to test and evaluate the validity of the design model against two existing war shelters based on four initial design intents: (1) design a model based on biomimetic principles; (2) create a modular system; (3) improve the comfort and protection of war shelters; (4) minimize green house gas emissions. Within each design intent, there are specific variables that distinguish themselves from one another. From these variables, one can immediately evaluate the positives and negatives of each war shelter model. A comparative analysis approach was implemented to compare and contrast the new model with two selected models. Based on specific sources and data, each of the variables was evaluated to an extent where a justifiable conclusion was reached.

11.6.2 Grounds of Comparison

The new war shelter model is designed to meet the present needs of an initial phase of construction in a contingency environment along with the intent for future improvement to meet the requirements for a temporary phase structure. Therefore, a small modular general purpose tent system (MGPTS) and a containerized housing unit (CHU) were selected for comparison. MGPTS are typically used during the organic and initial phase of a contingency operating base. However, in some transient locations where soldiers stay for only three to four days for in and out processing procedures, MGPTS are used in a more temporary status. In comparison, CHUs are typically used during the temporary phase and possibly extend to a semi-temporary phase depending on the duration of the operation. The reasoning behind the choices of these two models for comparison are (1) both structures are still commonly and widely used in current war zones; (2) both shelters possess the characteristics of an initial and temporary phase types of living standards; and (3) both examples differ in materials and type of construction. Though all three models varied in size and volume, the size is based on the unit of area per occupancy for consistency of measures. Comparison of the design model with these two similar yet different types of war shelters was intended to result in graphic displays of the strengths and weaknesses of each model, and also provide future improvement suggestions.

11.6.3 Methods of Analysis

In order to reach a more coherent and less subjective conclusion, a combination of both model simulation and a comparative analysis was utilized. The first analysis approach was through three-dimensional modeling in Rhino and then importing into Ecotect for thermal and air movement calculations. Given that the design model is not a complete enclosed space in comparison to the two existing models along with other unjustifiable variables; a clear and probable assessment was unable to reach. See Appendix H, I, & J for the detail results of each analysis conducted in Ecotect.

The second analysis approach is a less data driven and more descriptive approach. The method used is a comparative analysis followed by a graphical qualitative comparison using a radar chart, also known as a spider chart. A radar chart is a graphical method of displaying multiple categories in the form of a two-dimensional chart of three or more variables represented on the same radii. The purpose of the radar chart is to quickly illustrate and visualize the strengths and weaknesses of each model for comparison. Radar charts are a great approach to present dry information and observation in a visually interesting and meaningful way. Radar chart structures are often artificial in nature, which its flexibility to design the chart to best fit its intent and purpose.

Prior to the mapping of a radar chart, a type of scale and all pertinent variables must be identified. There are various levels of measurement when it comes to defining a type of scale. Radar charts are primarily used for ordinal measurements, where each variable are justifiable in some respect and all variables are on the same scale. Ordinal measurements represent order, but are not relative in size or degree of difference between the items measured. In this scale type, an order such as, good, better, and best is acceptable. For the purpose of this analysis, an order of low, medium, and high is used throughout the different variables for consistency and ease of comprehension. The outer point represents the "desired" and the center point represents the "undesired".

Though radar charts are useful, there are limitations. Depending on the detailed and levels of the scale order and form of justification, the outcome might not be as convincing and informative as one might intend. Therefore, it is important to note that the intent of the radar charts for this project evaluation is to simply highlight the characteristics of each model in a two-dimensional graph for ease of comparison and analysis. Although the selected scale type does not reflect quantitative measures, it gives a general picture of the pros and cons of each model.

11.6.4 Characteristics of Each Model

11.6.4.1 Modular General Purpose Tent System

Modular General Purpose Tent System (MGPTS) is a pole-supported modular structure that can be quickly erected under normal conditions. The tent structure is based on the concept of a tensioned fabric roof, which distributes wind, rain, and snow loads from the fabric directly to the support system. Available in three different sizes, the MGPTS is 18 feet wide and 7 feet high at the top of the sidewall. The MGPTS can be extended in 18-feet increments by adding intermediate modules. Initially designed for billeting and field service functions, the MGPTS can be used for environmental protection for personnel, command and support, and maintenance.

The MGPTS comes with many components. Some of the major components include the side poles, end poles, center poles, end sections, mid sections, and screen walls. The number of poles and sections vary according to overall size. A small MGPTS requires two end sections, six side poles, two end poles, and one center pole.

11.6.4.2 Containerized Housing Unit

The typical housing unit for soldiers deployed to Iraq is a containerized housing unit (CHU). Based on an ISO Standard 1161, the containerized housing units are aluminum boxes measuring approximately 22 feet by 8 feet. Each CHU has a door, window, top vent, power cabling, and air conditioner for summer heat. Each CHU living space contains a bed, an end table, and a wall locker. Floors are made out of linoleum for ease of cleaning.

Designed as a light construction, the structure consists of floor and roof frames and corner profiles. According to the U.S. Department of State, a CHU is expected to last for approximately five years with minimal operations and maintenance requirements and independent utility and communication connections. If the interior temperature reaches 75°F (24°C) and the exterior temperature reaches 100°F (38°C), a Heating, Ventilating, and Air Conditioning (HVAC) system will be designed in place.

Depending on the operation, a CHU may house four people or be split into two-person units. Sometimes, depending on the soldier’s rank, one person may occupy the entire unit. Showers and toilets are typically separate units, but there are CHUs that are equipped with a shower and toilet. Sometimes, CHUs are stacked two high or lined up in neatly organized rows. For protection from mortar, CHUs are often surrounded by bags of dirt and concrete T-walls.

11.6.4.3 Design Model

Inspired by the nine biomimetic principles extracted from the study of plants and animals in the desert, the design model is characterized by the burrowing into the ground, berming around the living space, and the modular roof and wall panel system. The modular panel system is designed to allow the flexibility of a variety of configurations to meet various user and functional needs. The design also includes a cot, a storage space, and a hanger/shelving system. The cot is designed to be able to convert into a chair when folded up.

11.6.5 Perceptions of Biomimetic Principles

Design inspired by nature as described in the research section is a new approach to a sustainable future. Emulating nature's forms, process, systems, or strategies and translating them into design principles allow innovators to solve human problems that are less harmful and more beneficial to the natural world. The design model is based on nine biomimetic principles from the desert environment with the intent to improve the comfort and protection of war shelters while minimizing the discharge of green house gas emissions. Each biomimetic principles possess unique architectural characteristics. This part of the analysis is to discover whether or not the MGPTS and CHU acquire any of the biomimetic principles. Figure 75 is a radar graph that represents each design model's relative connection to the nine biomimetic principles. The scale order is as such, low means the model has little to no indication of biomimetic principle; medium means the model has some indication of biomimetic principle; and high means the model is strictly based on biomimetic principle. Each principle is evaluated based on the following:

- Less surface area- area of roof
- Thicker Envelope-thickness of the enclosure
- Volume and form relationship-height of structure
- Parallel ridges-signs of ridge structure
- Material as a protection and heat reduction-Material R value
- Burrowing-depth below ground
- In-Between Space-signs of second skin layer
- Color-color of exterior walls

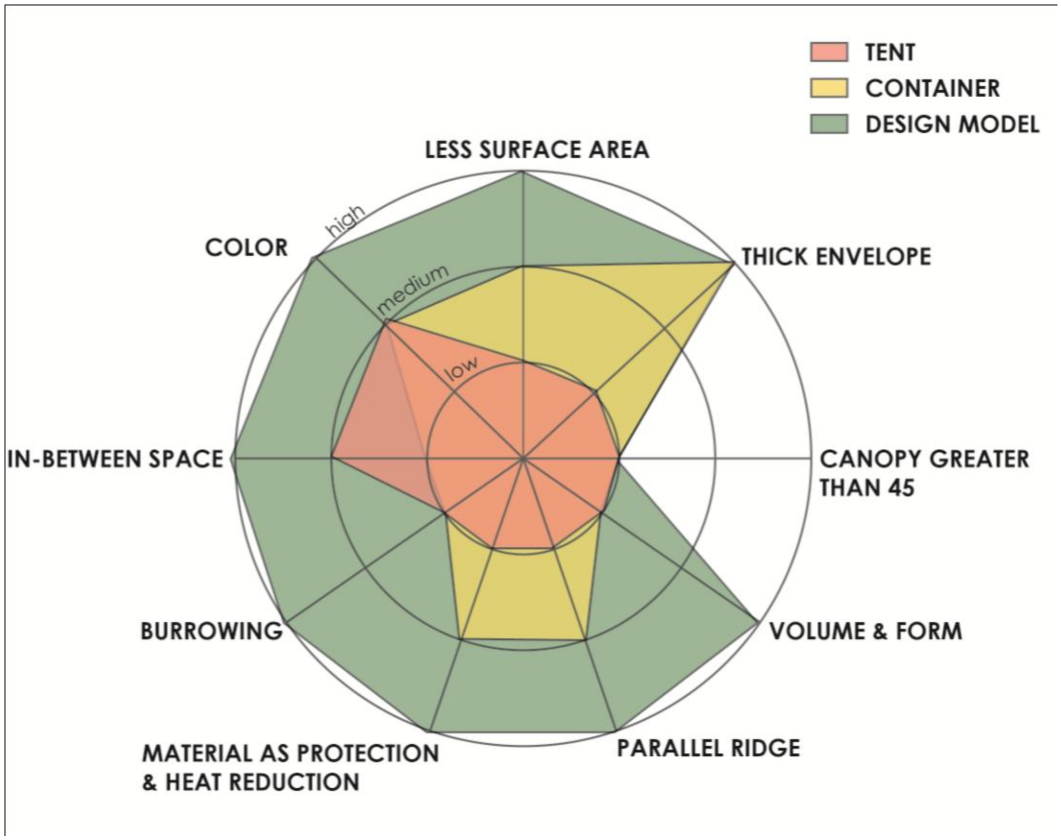


Figure 75: Biomimetic Principles Radar Chart Comparsion

11.6.5.1 Biomimetic Analysis

Based on the biomimetic principle radar chart (Figure 75), the two existing models reflect very little characteristics of biomimetic principles for obvious reasons. The CHU for instance is strictly based on a standard ISO shipping container, which is standardized and readily available in the industry. The MGPTS was designed primarily for efficiency purposes. Therefore, both the CHU and the MGPTS reflected very few characteristics of biomimetic principles in comparison to the design model. However, based on their individual material specifications, the CHU does indicate some biomimetic characteristics that are higher than the MGPTS, such as the thickness of the wall, corrugated ridges, higher insulation values, and less surface area. The CHU indicates the same value as the design model in terms of the thick envelope principle simply because the design model is not fully bermed with a thick enclosure while the CHU is enclosed all the way around. Both of the MGPTS and CHU are situated above ground and thereby do not reflect any signs of the burrowing principle. All three models reflect low indication of the biomimetic principle: canopy form greater than 45°. Providing a canopy greater than 45° is directly related to the preservation and conservation of water. Therefore, in future developments a canopy greater than 45° is beneficial for the integration of a water catchment system in the design.

11.6.6 Perceptions of Comfort & Protection

Comfort within a space can be perceived in many ways and is influenced by many variables. Based on a military contingency and a hot and dry climate environment, comfort is dependent on the thermal quality, air movement, cleanness, and personal factors. Thermal quality refers to the radiant heat and air temperature of a space. However, personal factors like an individual's health condition, activity level, personal space, and clothing level, can greatly alter the thermal comfort of a space. An individual's health, activity, and clothing levels vary from one to another; thereby the focus for person factor is the amount of personal space given per person. Air movement is defined by the rate of air flow within a space. Size, number, and location of openings can greatly improve the ventilation of a structure. Cleanness indicates the sanitary condition of the space. Though being clean is important factor for comfort. It is also critical to not the importance of cleanness varies depending on the duration of the operation. For example, cleanness during a short operation is less important in comparison to other factors like protection and thermal quality. This part of the analysis is to compare the comfort levels of each model based the different variables as discussed. Feeling a sense of being protected can also psychologically enhance the comfort level of a space. Protection is by the means of sheltering from the rain and heat, shielding from ballistic incomings, and guarding from insects and bugs. Figure 76 is a radar graph that represents an overview of the comfort level for each model. Figure 77 is a radar graph that further breaks down the element of protection into three comparative variables. Each variable is based on the scale order of low, medium, and high based on comfort level. Each variable is measured as such:

- Protection-thickness of wall
- Cleanness-quality of materials and interior finish
- Air movement-size and placement of windows
- Thermal quality-R value
- Personal Factor-area per person

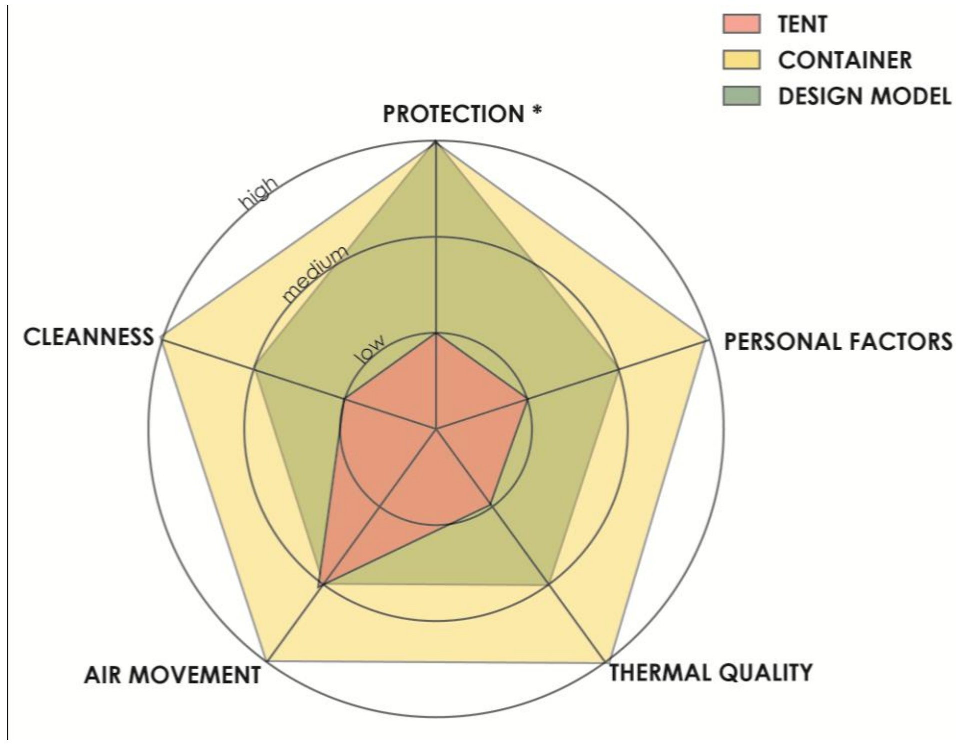


Figure 76: Comfort Radar Chart Comparison

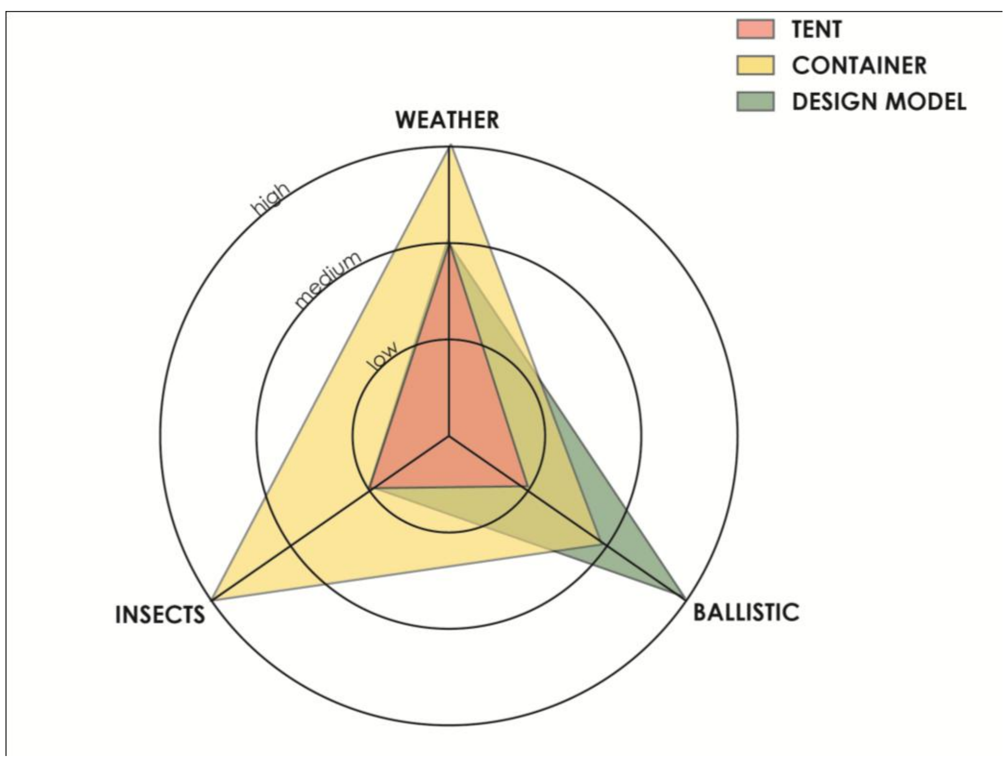


Figure 77: Protection Radar Chart Comparison *

11.6.6.1 Comfort & Protection Analysis

Based on the radar chart for comfort (Figure 76), the CHU seems to be the best model in terms of offering comfort while the MGPTS reflects the least in comfort and the design model is on the average. The CHU provides a high level of comfort primarily due to its all around steel enclosure supported of a HVAC system. The thermal and air circulation of the space can be easily adjusted with a HVAC system, thus creating a control environment. The interior is also nicely finished with an easy clean linoleum floor; therefore the cleanliness of the space is easier to maintain. In contrast, the site is the floor for the MGPTS and the design model is surrounded by soil and sandbags, which means the interior is not as clean. Finally, based on the personal space factor, the CHU averages about 80 square feet per person, the small MGPTS about 40 square feet person, and the design model about 55 square feet per person.

The protection category in the comfort radar chart is furthered broken down to three variables as illustrated in Figure 77. The CHU is high in terms of protection against the weather and insects and average in ballistic protection. Meanwhile, the design model is high in protection against ballistic incomings, but low in prevention of insects and average in protection from weather because of the exposed nature of its design to allow for natural ventilation. The MGPTS reflected low in both ballistic and insect protection. So overall, the CHU represented the highest in protection, follow by the design model and the MGPTS.

Although a HVAC system can be integrated to a MGPTS, it is generally not used. Beside the entry point, there are openings on the side that can be rolled up to allow natural ventilation-signs of air movement. Wherever the MGPTS is set up, the ground becomes the floor. However, depending on the duration of the operation, a wooden framed floor can be added to the MGPTS for cleanliness and durability. MGPTS is designed to house a large group of people. A small MGPTS accommodate in as many as 8 people or more, therefore in terms of personal space comfort and thermal quality, it is relatively low. In terms of protection, the MGPTS is low in comparison to the CHU and the design model because of its materiality.

The prototype is designed to be passively ventilated and cooled. Considering that the design model does not depend on a HVAC system for comfort, its overall comfort level is average. In terms of protection, it offers the greatest advantage in ballistic measures over the two existing models. Burrowing and berming not only serve as defensive measures, but also a great thermal regulator. The design model uses soil as a means of ballistic and environmental protection. Inspired by biomimetic principles, the characteristic of burrowing is proven to lower the surface temperature. Burrowing into the ground also reduces the amount of surface area exposure, thus minimizing the chance of being a target. Additionally, berming with the sand around the model provides a thicker envelope. Depending on the site, berming can be also used to shade the side with the most sun exposure or to direct air into the space from the prevailing wind direction.

Although there are advantages of the design model, there are some disadvantages. Since the design model requires a significant amount of ground work, site preparation appears to be a disadvantage compare to the two existing models. At least two personnel are required for a proper set up. One person need to dig while another person places the soil in sandbags.

Another possible disadvantage of the design model is the overall aesthetic of the interior space. Living in a hole might not seem as pleasant and comfortable in comparison to a finished linoleum floor of a CHU; but what you gain out of it is protection and thermal comfort without depending on a HVAC system. Depending on the duration of the operation, the spatial quality of the design model can be enhanced by adding more sandbags or possibly adding other eco-friendly materials to make the space more pleasant for living.

11.6.7 Perceptions of Modularity

The concept of modularity in architecture is typically defined as a system of standardized units or dimensions, for ease of assembly and repair or flexible arrangement and use. Modular design is becoming a more popular approach in military logistics for a number of reasons, ease of mobility, flexibility, adaptability, maintainability, and expandability. These variables can significantly improve the efficiency and performance of oversea military operations. A detail description of each variable is as follow:

Mobility refers to the movement of people and equipment from one location to another via ground, sea, or air transportation. Transportation plays a crucial role in the efforts to logistically facilitate an operation. Transportation simply means getting things from where they are at to where they are needed. Airlift is a major constraint in meeting current deployment objectives. A reduced footprint eases airlift requirement and fuel demand. Modular components and miniaturization increase lift capacity and movement efficiency. Air and space logistics are two key factors that govern military effectiveness. The three basic drivers of any transportation system are (1) how much material requires transportation, (2) how far the material needs to be transported, and (3) how fast a mode of transportation can deliver the material. Reduction in weight and size are two ways to reduce transportation requirements while meeting the objectives. Miniaturization, producing items smaller has also distinct logistical advantages. Smaller items are easier to store and transport. Such items also require less complex logistics system and allow greater ease of transportation.

In modular design, flexibility refers to the degree to which a system responds to change. Equipment flexibility has a direct relationship with force structure. The more flexible the equipment, the less force and man power are needed for construction, which in turn reduce construction time and improve efficiency.

Adaptability is characterized by a system's ability to respond to a user's needs. Adaptability differs from flexibility in that is focus is not on upgrading or changing system components, but on matching and modifying those components to meet existing requirements.

Maintainability is defined by the ease of repair, operation, and the life cycle of materials. Modular components provide the flexibility to replace parts. Modular components and construction improve the repair process and reduce the overall maintenance requirement. Durability of materials, thus become a critical factor for the extended life expectancy of the system.

Expandability is the ability to increase in size, volume, or quantity. The ability to expand in size and volume will give the military the flexibility to change and re-arrange troop organization based on site, protection, and time measures.

This portion of the analysis is to compare and contrast the modularity aspect of each model based on five variables. Figure 4 is a radar chart that summarizes the modularity spectrum of each model. The scale order again is based on low, medium, and high. Each variable is measure based on:

- Mobility-ease of transportation
- Flexibility-ease of construction
- Adaptability-multiple use of components
- Maintainability-ease of repair
- Expandability-ability to multiply and grow

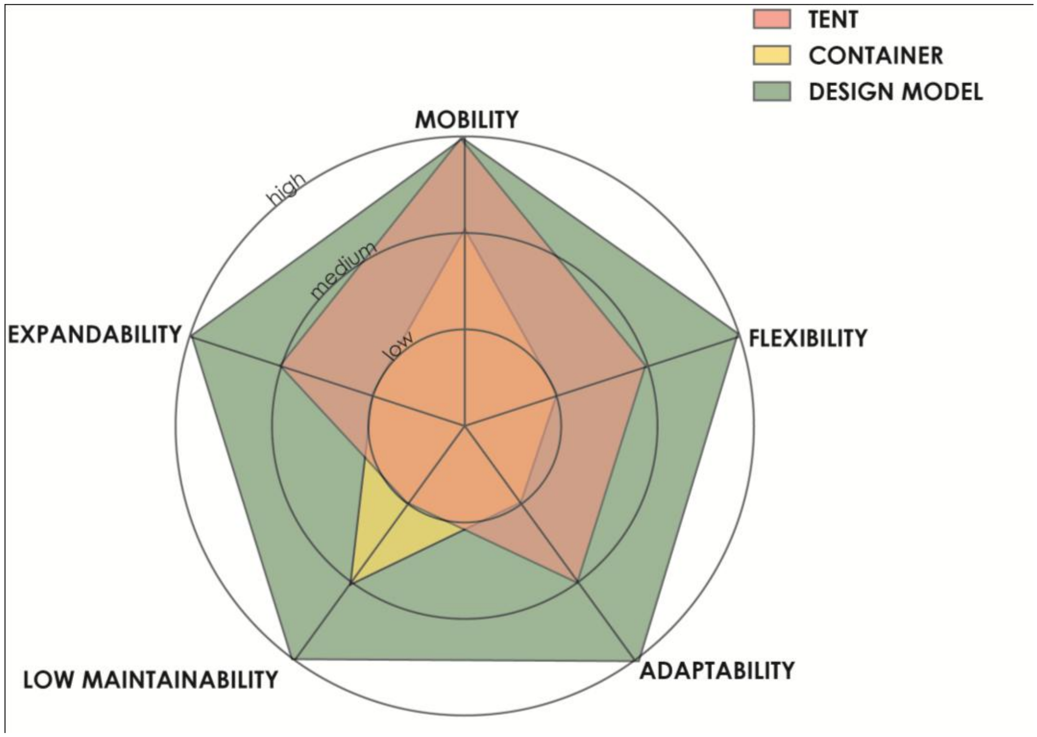


Figure 78: Modularity Radar Chart Comparison

11.6.7.1 Modularity Analysis

Base on the radar chart for modularity (Figure 78), the design model reflect the highest in modularity, follow by the MGPTS and then the CHU. Modularity and simplicity in construction are unique characteristics of which the design model is highly based on. The design model is based on a modular panelized buddy system, where each person carries half a shelter (three panels) and the combination of both half shelters (six panels) form a complete living space.

The panel system is also uniquely designed to improve the mobility, flexibility, adaptability, maintainability and expandability for ease of military logistics. The size of the panels (five feet by seven feet) is designed to stack on top of each other and fit perfectly in a cargo HMMWV (High Mobility Multipurpose Wheeled Vehicle) and a military aircraft cargo pallet for ease of mobility. In addition, the panels are divided into two types: A & B. Panel A serves as a wall system while Panel B functions as a roof system. The wall panel is secured into the ground by a stake and sandbag system. The stakes are also designed to serve as a hanging system to provide additional storage places. A cot/chair system is also integrated into the deign model to provide the basic needs of a sleeping and sitting area. Lastly, the panels are designed inconsideration of future growth and expandability. Additional panels can be grouped to form larger units for different types of use. Depending on the extent of the operation, the panels can be also be modified to provide a more durable structure. With minimal components and simplicity in construction, the design model is designed to improve many aspects of modularity.

The MGPTS is known for its modularity, light weight, and pole-supported structural system. Based on a modular length of 18 feet, the tent is flexible in configuration. Depending on the climate environment, the system can also accommodate an external environmental control unit like air conditioning. Since the parts are interchangeable, different size tents provide great flexibility for different types of use.

A key feature of the MGPTS is the quick setup time. A small tent takes about 27 minutes to set up with four personnel, a medium tent takes about 36 minutes with four personnel, and a large tent takes about two hours to set up with six personnel.

Another advantage of the tent is the size of the components. No parts are longer than 96 inches. In times of movement or storage, the components can fit into a standardized ISO container measuring 90 inches x 90 inches x 234 inches.

A disadvantage of the MGPTS is the complexity of the setup due to its multiple parts and components. A small MGPTS requires at least four personnel to set up. If one of the components is missing or broken, the MGPTS cannot be completed. Another disadvantage of a MGPTS is its high level in maintainability. Depending on how long the MGPTS is exposed to the outdoor environment, the material will deteriorate. The fabric may rip and tear, which requires patching work. Proper cleaning of the MGPTS is essential for the durability of the structure. The fabric sections must be dry before being folded and stored. MGPTS is designed for temporary use in nature and therefore does not meant to last through time. The MGPTS is also very complex in terms of construction. Compose of many individual parts in varying sizes; the set up of a MGPTS requires more than two people. Parts are also easy to lose and needs to be replace.

The beauty of a CHU lies in its universal standards. Based on the ISO standard container sizes of 8 feet wide, 20 or 40 feet long, and 8 feet 6 inches tall, the units are universal, which means they can be reused or resold anywhere in the world. Transportation of shipping container modules is made easier by the fact that shipping containers conform to shipping standards, allowing them to ship by rail, ship, or truck without overly specialized equipment. A container home requires minimal onsite setup and preparation work. Provided that the container is fully equipped, the container can be simply brought onsite and ready for use in a short amount of time. The military uses shipping containers due to their availability, low cost, standardized size, durability, and ease of transport.

Another advantage of a CHU over the MGPTS and design model is that the structure comes with all the essential living amenities in one package. Each insulated shipping container has a door, window, top vent, power cabling, and an air conditioner.

Despite its universal standard and great amenities, there are limitations and challenges. Even though it is based on an ISO container and can be easily transported to any parts of the world. The size is bulky and hard to manage. Setting up containerized units requires heavy machinery and lifting. Installation may require a crane to lift and place the container. A significant amount of ironwork is required if the containers have to be cut and welded in place to reinforce the structure. Moving containerized units from one location to another also demands a lot of manpower and is expensive. The size and shape of a CHU limits design flexibility and expandability. Given its standardized dimensions, the containers can be either stacked or placed side by side. Due to its rectangular form, the configuration will always be rectilinear.

12.6.8 Perceptions of Green House Gas Emissions

One of the largest contributors of green house gas emissions is the combustion of fossil fuels. Each year the military spends billions of dollars on energy cost. A significant amount of this cost is associated with overseas operations, which is a result of many factors like transportation, energy use, material production, and trash footprint. Transportation refers to the movement of military personnel and equipment to and from operating bases through air, sea, or ground. The number of personnel is pre-determine, therefore the focus here is the transportation of equipment. Hypothetically, the lighter and modular the equipment, the ease they are for transportation. Energy use refers to the demand of electricity use in a living unit. The integration of an air conditioning unit is likely to increases the level energy consumption. The production of materials also required high energy demand. Therefore, the minimal use of materials will help to reduce production cost and fossil fuel demand. The last factor considered was trash footprint, which refers to the accumulation of solid waste in landfills. The more equipment the military brings overseas, the more likely they will likely leave behind solid waste and turn to landfills. Solid waste treatment and disposal also produces green house gas emissions.

With the increasing concern of global warming and the rising cost of oil, cutting fossil fuel use can significantly minimize greenhouse gas emissions, reduce energy cost, and improve military operations. Therefore, a part of the analysis was to evaluate the energy efficiency of each model based on the four variables: transportation, electricity, material production, and carbon footprint. Each variable is measured as such:

- Transportation-size and weight
- Energy Use-electricity demand
- Material production-type of materials
- Trash Footprint-Use of materials

The scale order is identified as low, medium, and high.

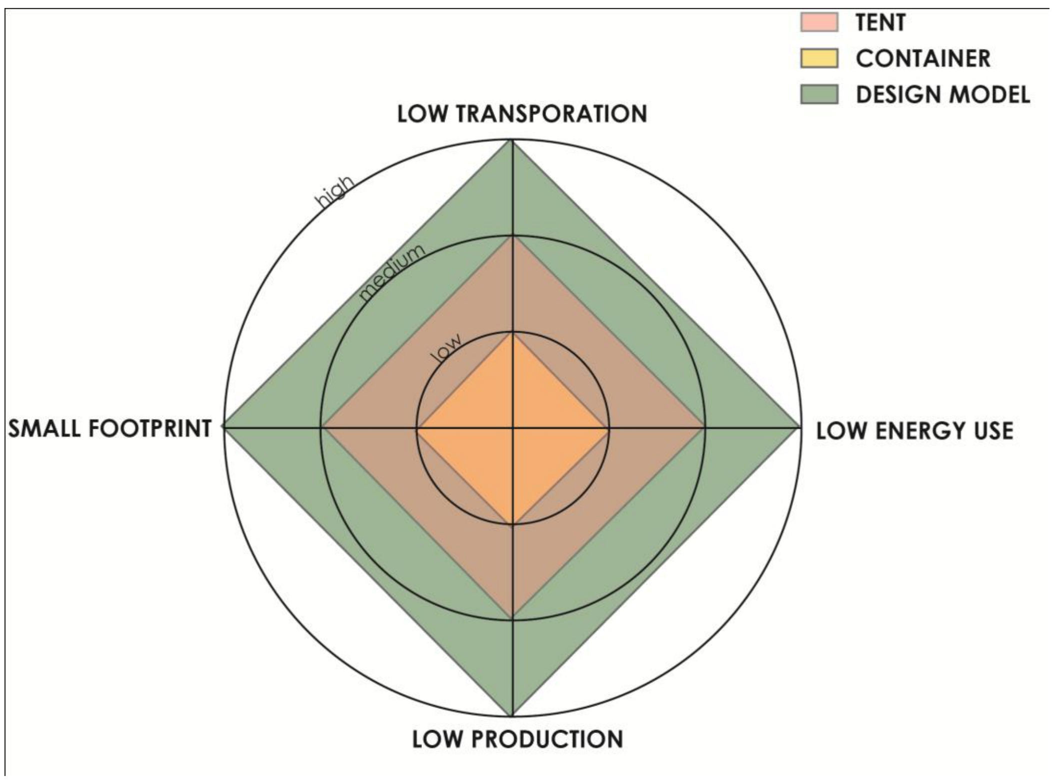


Figure 79: Low Greenhouse Gas Emission Radar Chart Comparison

11.6.8.1 Greenhouse Gas Emission Analysis

Base on the radar chart comparison for greenhouse gas emission (Figure 79), a CHU is heavily dependent on a HVAC system for thermal comfort; therefore the energy is definitely high. Both the MGPTS and design model are designed to be naturally ventilated. Although, depending on the outside temperature, a HVAC system can be integrated into the MGPTS. In terms of size and weight, the CHU is the heaviest and bulkiest of all, which requires more energy to produce and transport. In contrast, the MGPTS and design model are designed to be compact and able to fit in ISO containers, aircraft pallets, and typical cargo HMMWVs. Though a specific material is not identified for the design model, a new material that is light in weight and durable will be developed specifically for the model.

One of the greatest advantages of the design model is the minimal use of materials brought onsite. A significant portion of the design is based on the use of onsite materials, therefore the amount of energy required to transport materials to the site is minimized and the tendency to leave behind a large amount of waste is lessened. Both the CHU and the MGPTS are shipped to operating bases and do not use local materials, therefore requires high demand in energy consumption. The more equipment the military needs to import, the more likely waste will be left behind to be destroyed. Designed to be modular, naturally ventilated, and resourceful, the design model is the most energy efficient and reflects the lowest in terms of green house gas emissions.

11.6.9 Comparative Analysis Overview

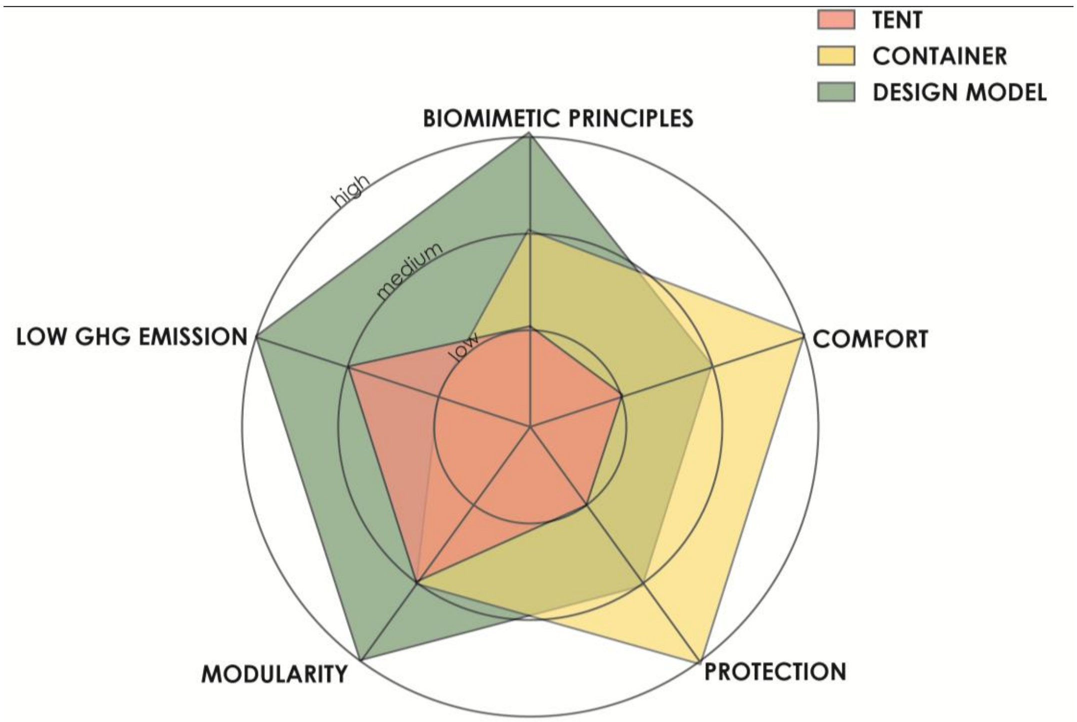


Figure 80: Comparative Analysis Radar Chart Overview

11.6.9.1 Summary of Comparative Analysis

Each model has its own strengths and weaknesses based on each of the five identified variables: biomimetic principles, comfort, protection, modularity, and green house gas emissions. Figure 80 is a radar chart that summarizes all of the analyzed variables and highlights the pros and cons of each model based on the four design intents. Based on the overview radar chart, one can conclude that there is not one single model that is dominant in all five identified variables. A CHU might be the highest in comfort and protection level, but is clearly a reflection of high energy use to monitor the comfort level within a space and the completely hard enclosure. The design model on the other hand might average in comfort and protection, but is the highest in biomimetic principles use and modularity, which resulted in the lowest in greenhouse gas emission. The design model is inspired by biomimicry principles; therefore the average in comfort and protection while maintaining the least in greenhouse gas emission indicates the value of biomimicry in green design. Due to the nature of its material, the MGPTS reflects low in protection, comfort, and the use of biomimetic principles. Lastly, all three models show signs of some level of modularity in their design, which indicates the importance of modularity in the augmentation of military logistics and contingency operations.

12. PROJECT EVALUATION AND FUTURE IMPLICATIONS

This doctoral project provides a platform for experimentation testing the possibility of improving the comfort and protection of troop housing in a desert contingency environment inspired by biomimetic examples. The design looks to plants and animals that live in desert environments for solutions to dwelling in extreme heat. This design attempts to demonstrate the value of biomimicry in helping to improve housing conditions in a desert contingency environment and minimize dependency on air conditioning and greenhouse gas emissions. The comparative analysis radar chart provided a great overview of the pros and cons of each model based on the five categories: biomimetic principles, comfort, protection, modularity, and low greenhouse gas emissions. The five categories are derived from the four design intents of which the design is based on. Each category was included for its importance to the design, its relationship to the long-term benefits to the military, and its impact on global warming.

The design example attempts to address each category to a certain degree. For the comfort and protection aspects, the design example was inspired by the nine biomimetic principles identified from the research of how plants and animals adapt to the hot and dry climate in the desert. Though some biomimetic principles are represented more than others, all nine were considered throughout the design process. The principles of burrowing and less surface area work hand in hand. Burrowing into the ground reduces the amount of surface exposure, which in turn helps to reduce heat radiation. Berming around the perimeter allows for a thicker envelope for thermal regulation and protection. The parallel ridges of a barrel cactus inspired a ridged profile panel that offers strength and can potentially help to harvest water. The curved form and color of the canopy allows the model to blend into the desert environment. Finally, the functions of spines and fur initiated the idea of creating a double layer to reduce heat gain by lowering the solar radiation from the roof.

Protection is a major safety issue in a combat related environment. Burrowing into the ground for heat mitigation provides an opportunity to use the excess soil to form a thicker envelope around the shelter. The soil can also be placed into sandbags for improvement of the living area. Another advantage of burrowing into the ground is minimizing the amount of surface area exposure, which reduces the possibility of enemy identification. The curvilinear form of the structure also helps blend it into the desert environment. Lastly, the color of the structure mimics the light shaded tone of the plants found in the desert environment. Together, these characteristics ensure a protective design shelter.

Logistics, and the movement and maintenance of materials, equipment, and forces are important aspects of military operations. Therefore, the design example also focuses on the issue of transportability and constructability. The design model is based on a panelized system with a simple locking mechanism. Each person is issued three panels and two people can put together a basic living shelter. Various configurations are explored to demonstrate the potential use of the panels in the future.

Another great benefit of using the idea of burrowing is the use of onsite materials, which decreases the need to import foreign materials and the chance of leaving unnecessary waste. The movement of equipment requires a significant amount of energy and oil cost, therefore the minimization of materials will not only reduce the logistic cost, but also decrease the consumption of fossil fuel.

To validate whether the biomimetic principles will help to improve the comfort of the space while minimizing dependency on traditional mechanically controlled systems, various simulations were conducted into Ecotect to calculate thermal analysis, solar radiation, and wind patterns. The design model was tested against two existing models: a containerized unit, and a small modular general purpose tent system.

The results of the simulations and calculations in Ecotect were not sufficient to make a justifiable conclusion for a number of reasons: (1) the design is not a complete enclosed space; (2) Insufficient material data; (3) size and number of occupants vary among the models; (4) too many design variables to consider; and (5) incompetence in the use of the modeling and analysis software. However, the burrowing analysis reflected a signs of improvement in thermal comfort. Meanwhile, the CFD analysis provided some interesting data to improve the air movement within the space. In the end, a more generalized approach, using a radar chart comparative analysis was conducted. The benefit of a radar chart analysis is that multiple variables are compare, which allows one to make a justifiable conclusion. The radar chart can be further supported by a set of quantitative measures. Although an ordinal approach was use for the comparison of the three war shelters, it still provided an overview of the pros and cons of the each models. More importantly, it supports the hypthesis that a design model that provides comfort and protection can be achieved using biomimetic principles that minimize greenhouse gas emissions.

The design example also addresses the issues of environmental responsiveness. The design considers the prevailing wind direction and solar orientation. The placement of the berms is an indication of where the wind generally comes from and where the most direct sunlight hits. The key is to maximize the available renewable resources in order to bring comfort and protection into the space. Depending on the site location, water catchment may provide another cooling element. Harvesting water in Kuwait for instance might be challenging due to the unpredicted rain pattern and dry climate conditions. For future exploration, the idea of harvesting solar power is also worth evaluating. The dry and hot desert is abundant in solar energy; therefore, the idea of harnessing electricity through photovoltaic panels or dye solar cell technology would allow the war model to be much more self-sustaining and efficient. Maximizing the use of renewable energy resources is an alternative means of meeting our high energy needs while reducing the demand for fossil fuels and greenhouse gas emissions.

In addition to the design aspects, the construction process is also an important consideration for the project. Over the course of a contingency operation, troop housing transitions from temporary shelters like tents to more permanent structures like container housing. The movement of troops and housing consumes a lot of fuel energy. Therefore, the project looks into modularity and local resources to reduce the energy consumption due to transportation, which in turn will help to reduce greenhouse gas emissions.

The process of research, analysis, and design exploration provides a framework for the final design model. As simple as the project might seem, many challenges arose. One of the biggest challenges was interpreting the biomimicry principle and finding a correlation to the standards of military construction. Attempting to apply the nine biomimetic principles was not an easy task, but luckily, they all work hand in hand with each other. A key solution to survival in the desert is heat reduction, which is a strong characteristic of the design model. Another challenge was trying balance efficiency and innovation. As the design gets more technical, the connection with biomimicry often becomes less clear. Finally, the process of conducting the simulations and analysis was difficult. In order to do a proper analysis in Ecotect, there are many factors to consider. One setting might completely throw off the data. Therefore, controlling the data input was very important. Though the results from the simulation did not turn out as expected, it is evident that the practice of biomimicry does help to improve the thermal comfort of a space.

13. FUTURE EXPLORATION

In the process of design and research, new biomimetic ideas and inspirations emerged for future design exploration. For example, the Stenocara beetle in the Namib Desert, one of the hottest places on Earth, survives by using its bumpy shell to draw drinking water from periodic fog-laden winds. Scientists at the British Ministry of Defense are mimicking the shell's architecture to design more efficient water-harvesting techniques. Researchers from MIT have also discovered a tiny deep sea snail called Crysmallon Squamiferum that could give way to tough, lightweight body armor. The snail has a unique three-layered shell that can easily fend off attacks from crabs.

13.1 Stenocara

The surface of Stenocara's armor-like shell is covered with bumps (Figure 81). The peak of each bump is smooth, like glass, and attracts water. The slopes of each bump, and the troughs in between, are covered with wax, which repels water, like Teflon. As the early morning fog sweeps across the desert floor, the water sticks to the peaks of the beetle's bumps, eventually forming droplets. When the droplets become large and heavy enough, they roll down from the tops of the peaks and are channeled to a spot on the beetle's back that leads straight to its mouth. This water-collecting ability is critical to the beetle's survival because the Namib Desert is one of the most inhospitable places on Earth, with scorching sands that can reach 60°C (140°F). Stenocara's bumpy shell serves as an ideal design model for designing inexpensive tent coverings and roof tiles that could collect water for drinking and agriculture in arid regions.

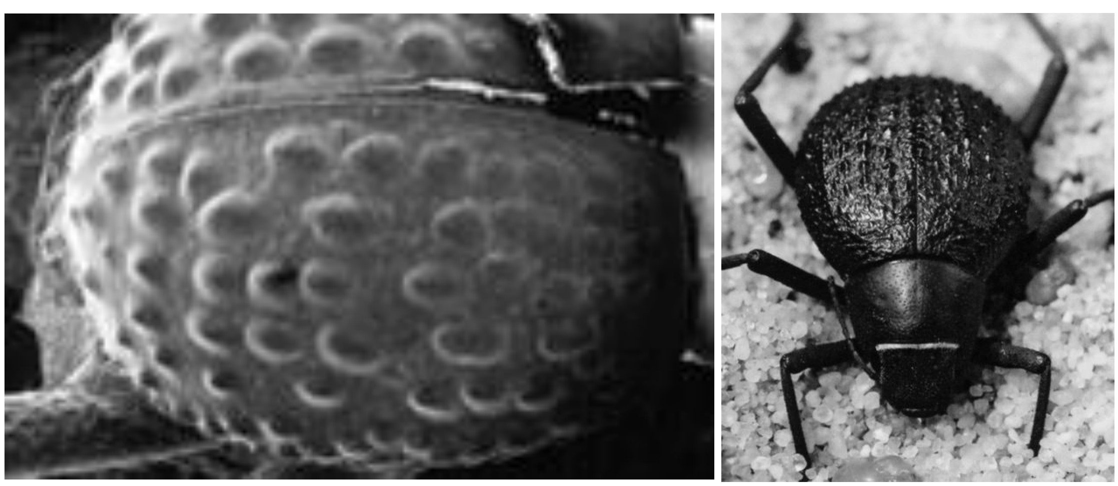


Figure 81: Stenocara Inspiration

13.2 Pill Millipedepe

As a way to protect themselves from predators, the pill millipede rolls its jointed skeleton into an impregnable ball. The twelve body segments are dome-shaped in cross section. The pill millipede's joint system may be an inspiration for deployable and protective domes and tent structures (Figure 82).

Figure 82: Pill Millipedepe

13.3 Lionfish

The lionfish is characterized by its beautiful stripe patterns (Figure 83). "The strange appearance of the lionfish is caused by its highly divided dorsal and pectoral fins. At close range its striking colors are a warning to predators that it is poisonous: both these groups of fins can inject poison. The striped patterns also serve to break up the outline of the fish when viewed from a distance, a form of camouflage." (Foy and Oxford Scientific Films 1982-187). The lionfish's camouflage technique serves as inspiration for communication towers and wind turbines, high-security military sites, and has agricultural applications (deterring or controlling pests).

Figure 83: Lionfish Inspiration

13.4 Sea Snail Shell

An MIT study found that the iron-plated shell of the scaly-foot snail may provide advanced protection due to the way it dissipates mechanical energy. The three-layered shell might lead to improved armor for soldiers and military vehicles (Figure 84).

Figure 84: Sea Snail Shell

13.5 Ask Nature.org

There are new biological discoveries every day. Asknature.org is an online biomimicry design portal that brings designers, architects, engineers, and scientists together to create a large database of biological ideas. Their goal is "to connect innovative minds with life's best ideas, and in the process, inspire technologies that create conditions conducive to life."[68] With over 1,200 strategies identified in its database, Asknature.org is a great source of inspiration for future design exploration.

68 "Ask Nature - the Biomimicry Design Portal: biomimetics, architecture, biology, innovation inspired by nature, industrial design - Ask Nature - the Biomimicry Design Portal: biomimetics, architecture, biology, innovation inspired by nature, industrial design." Ask Nature - the Biomimicry Design Portal: biomimetics, architecture, biology, innovation inspired by nature, industrial design - Ask Nature - the Biomimicry Design Portal: biomimetics, architecture, biology, innovation inspired by nature, industrial design. http://www.asknature.org/

CONCLUSION

Besides the physical, mental, and emotional issues that U.S. soldiers face every day, they are also challenged by the stress and danger created by terrorists and the nature of the environment in which they are deployed. On top of that, soldiers have to fight climates and climate change, which can greatly affect their living and working environment. Air conditioning may be a great temporary solution for indoor thermal regulation, but it is definitely not the most eco-friendly way due to its high energy consumption and required maintenance. The dependency on HVAC system for comfort will further aggravate the problem of global warming.

Based on personal experience in Iraq and the survey conducted in this research, housing was proven to be one of the main factors affecting the quality of life for soldiers deployed to the Middle East. The Middle East is characterized by its extreme desert environment conditions. Thousands of troops continue to be mobilized to the Middle East in support of OIF and OEF and considering that one fifth of the world's land surface are deserts, the scope of this project centered in development of a war shelter for a desert environment. There are obviously many variables that can influence the quality of living standards in a desert; but the focus of this project was primarily on the improvement of thermal comfort and protection for troop housing.

Troop housings in the military are governed by different construction standards of which are dependent on the type and extent of the operation. These standards are often driven by efficiency of military logistics. Focus on specific site conditions rather than on a specific locality, this project's intended use is for contingency bases. Contingency operations are temporary in nature. There are typically three phases of construction for a contingency operation: organic, initial, and temporary. Each phase of construction is characterized by different type of structures and tier levels. The design model is proposed to meet the requirements of an initial phase of construction with the intent that the model can be modified in to meet future demands.

In the evolution of architecture, many building components have been borrowed from the study of plant and animal forms, patterns, structures, and systems. Today, this approach is widely known as biomimicry, a new science that studies nature's models and translates them into design and building principles. Biomimicry can be used as a guiding principle that will result in more efficient and functional designs that are supportive of the natural environment.

Nature has evolved to withstand the changing environment. Desert plants and animals are able to adapt to the hot, dry, and cold environment by using both physical and behavioral mechanisms. Cacti are among the most desert-adaptive plants due to their absence of leaves, shallow root systems, ability to expand and contract to store water in their stems, spines for shade, and thick waxy skin to seal in moisture. Desert animals depend on burrowing habits, the ability to change skin color, and a thick layer of fur for survival in hot desert environments. Animal structures also face similar architectural challenges as manmade buildings such as protection, ventilation, structural complexity, and space programming.

Biomimetic approach in design is about searching in nature for common problems and solutions that are applicable to human beings. Solutions are often found at the site of where a problem is originated. The study of how desert plants and animals adapt to a xeric environment resulted in nine biomimetic design principle that provided different means of achieving comfort and protection in a desert environment. The nine biomimetic principles established the initial concept of the new war shelter design model. Further interpretation of the nine biomimetic principles in the form of a matrix elaborated on the principle's application to design with regards to providing comfort, protection, and sustainable strategy. A contingency construction phase matrix was also created to illustrate the past and present types of war shelters follow by the proposal of future war shelters based on biomimetic principles. Both matrixes outline the foundation by which the design model is supported by.

The final design proposal is a synthesis of three important aspects of the research: the recognition of global warming challenges, the confinement of military standards, and the interpretation of nine biomimetic design principles extracted from the study of desert plants and animals. The base of research resulted in four main design intents for the project: (1) design a contingency military shelter based on biomimetic principles; (2) create a modular system as a way to improve the mobility, flexibility, maintainability, adaptability, and expandability of the troop shelters for the ease of military logistics, (3) improve the comfort and protection of war shelters in a contingency environment, and (4) minimize greenhouse gas emissions. The four design intents not only created a framework for the design project, but provided a frame of reference for a detail comparative analysis.

With an overall concept of blending in with the environment, the design model is characterized by the idea of burrowing into the ground to reduce surface temperature; utilizing the excavated soil to berm around the site for protection and shading; a parallel ridge panel profile to minimize the amount of solar radiation and heat gain; a double insulated roof system to reduce transfer of heat; a greenish gray roof color to minimize solar radiation; a low arch profile that blends in with the undulating sand dune, and a modular panelized roof and wall system for efficiency in military logistics.

To test the hypothesis and analyze the strengths and weaknesses of the design model, both a simulation and a comparative analysis were conducted. The design model was tested against two commonly used war shelters today: a containerized housing unit (CHU) and a small modular general purpose tent system (MGPTS). Due to the difference in nature of each model and the limited knowledge of material specifications, the simulated data did not provide enough of evidences to make an overall convincing conclusion. However, the technique of burrowing based on the simulation did indicate an improvement in thermal comfort. Computational fluid dynamics also suggested that the proper orientation of the model and height of the berms can make a difference the air flow rate and movement of a space. Additional research on materials is recommended for proper Ecotect analysis and simulation.

Provided that the design model was based on four clearly identified design intents, a comparative analysis utilizing a radar chart to compare the different variables of each the intent was completed. Based on scale order of low, medium, and high, each variable was carefully analyzed. Since all variables were considered in the analysis, it provided a great overview of the strengths and weaknesses of each model. A CHU reflected the highest in comfort level, but is also the highest in greenhouse gas emissions due its dependency on a HVAC system to monitor temperature and air circulation. On the other hand, the design model reflected the highest in the use of biomimetic principles, protection, and modularity; average in comfort, and the lowest in greenhouse gas emissions. Finally, the MGPTS reflected lowest in almost all the categories due to the weak nature of its material. All three models reflected some levels of modularity in their design, which indicates the importance of modularity in the augmentation of military logistics and improvement of contingency operations.

From the combination of computer modeling and simulation and a comparative analysis, one can conclude that biomimetic principles can serve as an alternative approach to traditional energy dependent control system, which in turn can reduce our dependency on fossil fuels and minimize the impact of greenhouse gas emissions on global climate change. The design principle of burrowing in particular demonstrated an obvious improvement of thermal comfort and protection from environmental factors and ballistic impact. Given the relevance of burrowing in respect to thermal comfort and protection, it is recommended that rather than using burrowing during the initial phase of construction, burrowing should be use in all aspect of military construction in a desert contingency environment. Though the process of burrowing might be labor intensive and the level of comfort might not meet the quality of a CHU power by an HVAC system, these two factors can improve in a matter technology, funding, and design development. A tractor for instance can significantly speed up the process of construction while the increase of funding and further development of the design can drastically improve the overall comfort level of the interior. Meanwhile, it is also important to consider that in times of war and in a danger zone, what are more important, aesthetic appearance of the interior or the comfort and protection of the structure? Lastly, modularity is an important factor to consider in design of military structures. Not only does it help to improve the efficiency of military logistics, but also aid the reduction of fossil fuel use and minimize the impact of greenhouse gas emissions on global climate change.

Biomimicy is a very scientific design approach where project ideas are often the replica of specific biological models. These ideas in almost all cases require intensive research and dissection of a particular plant, animal, or organism to fully understand the potential of each system and its application to the design challenge. Though each principle highlighted in this project is a derivative of a particular strategy used by desert plants and animals to adapt to the arid environment, these principles can be further broken down to specific quantifiable components that could be measure. For instance, the form and volume relationship of a Saguaro Cactus in response to climatic conditions could be further explored. One of the greatest advantages about the biomimicry process is to be able to test the biological models like a scientific experiment. In the process of design, focusing on nine different biomimetic principles was definitely a challenging task. Then, during the simulation and analysis portion, it was even more difficult because the simulation in Ecotect required detail understanding of the materials and the comparative analysis required a quantitative scale for a more qualitative evaluation. For future biomimicry implications, focus and explore on one biomimetic principle at a time; dissect the biological principle to its core measureable elements; and seek specialized scientists on challenging topics to save research time. Like any scientific research, biomimicry is an on-going process and development.

The project focused on an arid climate environment rather than a specific site locality. The biomimetic approach of studying how desert plants and animals mitigate the extreme temperature of the environment resulted in nine design principles, which led to the final design the new war shelter. Throughout the entire biomimetic design process, climate was the primarily driven factor; however another important aspect of this project is the military component. In process of design and additional research, new biomimetic principles arose from different site environment. For instance, the stripe patterns of a lionfish can serve as a form of camouflage for protection and layers of a sea snail shell can become a material with great strength. New biological models are being discovered every day. Therefore, for future biomimetic researchers and designers, looking beyond its own site environment for inspiration in design might result in more applicable and better design solutions for similar problems.

Biomimicry is a relatively new discipline and is open to many different interpretations. Unlike other design approaches, biomimicry is research and scientific driven, which means it is a less subjective and more valid approach to green design solutions. Animals and plants face many similar challenges as human beings encounter. There is more than one answer to a problem that can be found in nature. The study of how different plants and animals adapt to the extreme condition of the desert resulted in a biomimetic design model that is site-sensitive, resourceful, and environmentally responsible. Biomimicry proves to be a valuable design alternative for future green design solutions.

The design example provided is not the ultimate solution for the improvement of war shelters in a contingency environment. It also serves as an experiment and exploration of the many possibilities that nature can provide to improve the comfort and protection for troop housing in a desert contingency environment. Beyond the military, millions of people around the globe are challenged by the impact of global warming on the thermal comfort of their homes and offices. If the biomimetic design model, as demonstrated here, can offer significant improvement of comfort and protection even in the greatly limited case of military troop housing, the benefits would be far greater if biomimetic principles become common to all aspects of architectural design. Biomimicry is the ideal sustainable approach to improve our world through designs that take advantages of nature's time tested ingenuity.

PART IV: APPENDICES

APPENDIX A: GLOBAL SURFACE AIR TEMPERATURE CHANGES

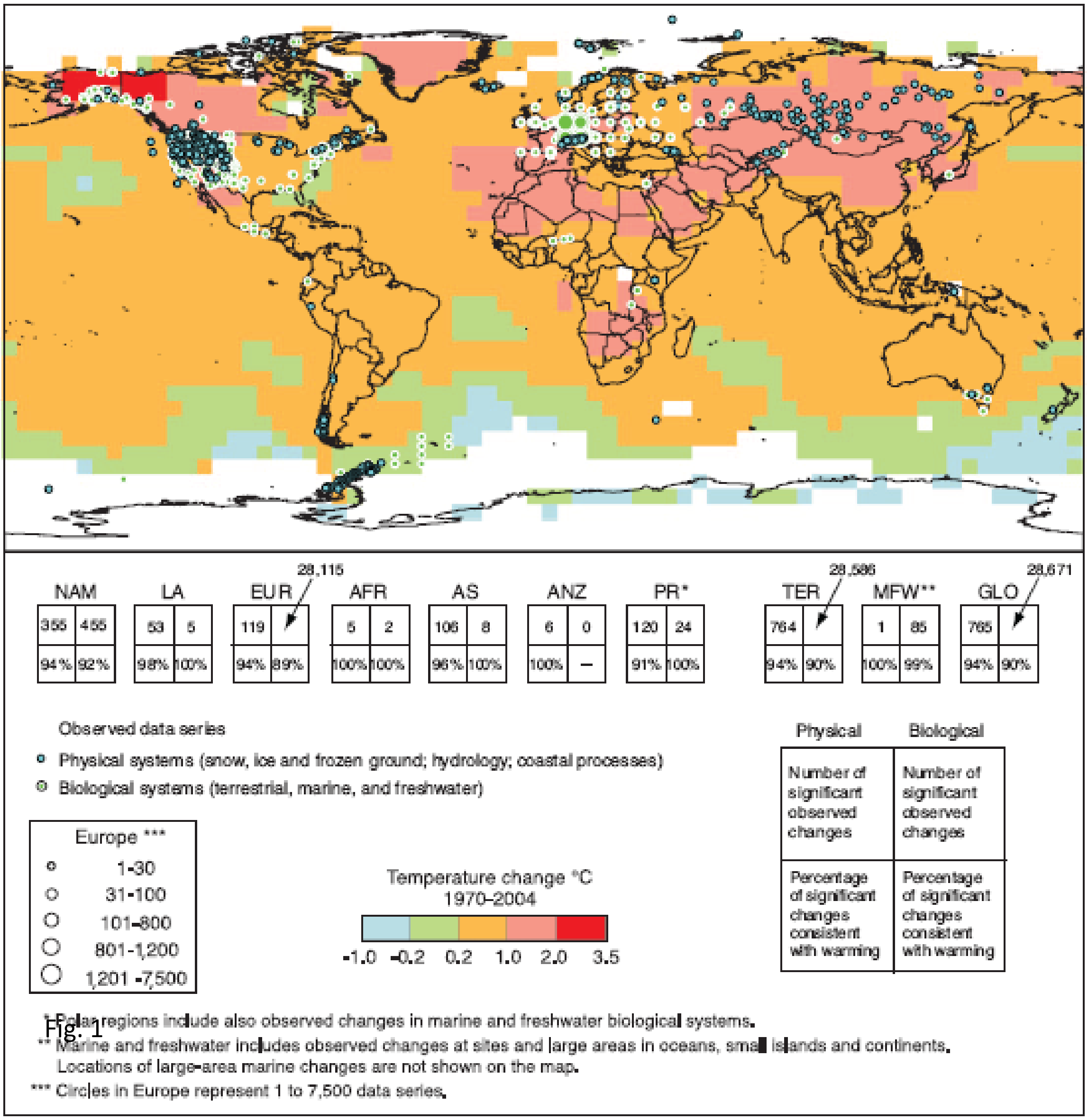


Fig. 1

Appendix A documents the locations of significant changes in data series of physical systems and biological systems along with surface air temperature changes around the world over the period 1970-2004.

APPENDIX B: INITIAL AND END STATE OF EACH TYPE OF FACILITY

Appendix B shows the initial and end state for each type of facility built at each main base camp.

Facility	Initial	End State
Housing	Tier I Tent	SEAhuts or Container
Latrine	Chemical	AB units or SEAhut
Shower	Tent	AB units or SEAhut
Septic	Lagoon	Treatment Plant
Office	Tier I Tent	SEAhut or Container
Helipad	M2 Matting	Concrete
Aviation Fuel	HMMT Tanker	Steel Lines and Tanks
Aviation Maint	Tent	Clamshell Tent
Runway	Gravel	Paved
Taxiway	Gravel	Paved
Medical	Medical Tents	SEAhuts or Metal Prefab
Kennel	Container	Wood Frame on Concrete
Storage	MILVANs	Warehouses
DRMO	Tent	Metal Prefab, Gravel Lot
Roads	Gravel	Asphalt
Water	Bottle	Wells, Treatment Plants
Fuel	Bags	Metal Tanks
Wash Rack	Gravel	Elevated Rack, Oil Water Sep
Electric	Generator	Local Power, Gen Back Up
DFAC	MKT Trailer	SEAhut
Ed Center	Tent	SEAhut
Post Office	Tent	Metal Prefab
PX	Tent	Metal Prefab
Barber	Tent	SEAhuts or Container
Alteration	Tent	SEAhuts or Container
Pressing	Tent	SEAhuts or Container
Laundry	Tent	SEAhuts or Container
Fire	Tent	Metal Prefab
Fitness Center	Tent	SEAhut / Metal Prefab
Field House	Tent	Metal Prefab
Athletic Fields	None	Grassed Fields with Lights
Communiuty Center	Tent	Metal Prefab
Theater	Tent	Metal Prefab
Chapel	Chapel-in-a-Box	SEAhut
Perimeter Fence	Triple Standard	NATO Std (Chain Link w/outrigger)
Perimeter Lights	Gen Sets	Fixed Lighting

APPENDIX C: CONTINGENCY BASE CAMP STANDARDS

Figure 5.1 - CONTINGENCY BASE CAMP STANDARDS

Support Facilities

Facility	Initial		Temporary	Comments
	Expeditionary	Initial		
Housing+	Unit Tents **	Unit/HF-FP Tents	HF-FP Tents to SEAhuts#	DV qtrs @ sustainment bases
Latrine	Burn out	Chemical	AB units/SEAhut	Planning Factor 1:20 PN
Shower	Shower Unit Tent	Shower Unit Tent	AB units/SEAhut	Planning Factor 1:20 PN
Sewage Disposal	Leech Fld/Lagoon	Leech Field/Lagoon	Lagoon/Treatment Plant	
Office	Unit Tents**	Unit/HF-FP Tents	SEAhut# or Container	
Helipad	Stabilized Earth	AM2 Matting	Concrete	Minimum, one Helipad w/landing lights
Fuel	Bladder	Bladder	Bladder	
Vehicle Maintenance	Unit Tent**	Unit/HF-FP Tents	Clamshell	
Vehicle hard stands	Stabilized Earth	Gravel	Concrete	
Medical***	Unit Tents**	Medical Tents	HF-FP Tents to SEAhuts	
Morgue	Unit Tents**	Refrigerated Cont.	SEAhut or Container	
Kennel	None	Container	Container (incl exercise area)	
Storage	Unit Tents**	MILVANs	MILVANs	
DRMO	Tent	Unit/HF-FP Tents	Metal Prefab, Gravel	
Roads/Streets	Stabilized Earth	Gravel	Gravel	
Potable Water	Bottle	Bottle/ROWPU	Well, Treatment Plants	
Non-Potable Water	Local Source	Local Source	Local Source	
Wash Rack	None	Gravel	Gravel	
Electric	Unit Generators	Prime Power/Contract	Local Power, Gen Back Up	
DFAC	Unit Tent**	Unit/HF-FP Tents	HF-FP Tents to SEAhuts#	
Ed Center	None	Unit/HF-FP Tents	HF-FP Tents to SEAhuts#	
Post Office	Unit Tent**	Unit/HF-FP Tents	Metal Prefab	
PX / Warehouse	Unit Tent**	Unit/HF-FP Tents	Metal Prefab	
Barber	Unit Tent**	Unit/HF-FP Tents	HF-FP Tents to SEAhuts	
Alteration	None	Unit/HF-FP Tents	HF-FP Tents to SEAhuts	
Pressing	None	Unit/HF-FP Tents	HF-FP Tents to SEAhuts	
Laundry	None	Unit/HF-FP Tents	HF-FP Tents to SEAhuts	
Fire	None	Unit/HF-FP Tents	Metal Prefab	
Fitness Center	None	Unit/HF-FP Tents	HF-FP Tents to SEAhuts#	

(Charts extracted from the 2007 Red Book)

APPENDIX C: DESIGN CONSIDERATIONS

Design Considerations

Facility	Type	Grade	NSF/person	Notes
Housing		E1-7, WO-1/3, O-1/4	80	
		E8/9, CW-4/5, O-5/6	160	
		O7+	256	
	Showers			1:20 person
	Toilets			1:20 person
		Distinguished Visitors	2944/DV Qtrs	
Office Space	Private Office	O7 – O8	300	
		O5-O6 Commanders, TF E9	200	
		O5, 04 CDRs, CMD E9	150	
		O4, O3 CDRS, Staff E9, Unit E8	100	
	Open Office	E8, WO, O1-3	110	
		E7	90	
		E1-6	60	
	General Space	HQ Temp	+40% of NSF	Total Building
Medical	Unit Aid Station		700/1000	
	Clinic		3200/1000	
	Medical		2100	+100/add'l Doctor
	Dental		640	+115/add'l Dentist
	Holding		460	+80/add'l holding bed
Special Med Factors	Separate Mech Space		+11% of NSF	
	Circulation		+35% of NSF	
	Walls & Partitions		+12% of NSF	
	Half Areas		+1.5 of NSF	
Motor Maintenance	Fixed Facility		1200/200	
	Administration		320/200	
	Pads			Large enough to accommodate largest unit + recovery vehicle
	Wash Rack			60' L w/oil water separator. Designed to accommodate largest vehicle
	Direct Support		1000/1000	
Kennels	Interior Facilities		145/dog	Kitchen, tack room, interior dog run
	Exterior Dog Run		48/dog	
DRMO	Recycling Facility		1	
	Gravel Holding Yard		2	Authorized strength
DFAC	Dining Room		860/100	
	Kitchen/Admin/Storage		430/100	
Religious Support			1624	
Education Centers			1710	
Mail Rooms			340	
AAFES				
	Barber/Beauty		240/1000	
	Alteration Pressing		160/1000	
	Post/Base Exchange		2800/1000	
	Warehouse		1340/1000	
	Administration		340/1000	
	Food Concession		640/1000	Each Food Concession
	Dining/Seating		500/1000	
	Laundry Collection		1024/1000	
MWR			3	3000 NSF per 1000 person
	Field House		Basketball	Full Size Court of 50' by 94'
	Volley Ball			
	Outdoor Basketball			paved
	Running Trail w/Stations(8)		2 miles	*operations allow
	Community Activity		2400/1000	
	Multipurpose Theater		1 facility/1000	
	Warehouse Maintenance		1/1	

APPENDIX D: SAMPLE OF SURVEY

Quality of Life of U.S. Soldiers deployed to the Middle East

PURPOSE

The purpose of this survey is to assess the quality of life and determine if there are opportunities to improve the quality of life for U.S. forces operating in the Middle East. This survey is conducted for independent research only and is not affiliated with the U.S. government.

PRIVACY STATEMENT

This survey is done only on a voluntarily basis. You are not asked to provide any information that can easily identify you. Therefore, you will not be personally identified.

1. When was your last deployment/ where/ and for how long?

2. What is your Rank?

3. Which of the following are the 3 most important factors affecting your quality of life at your last camp? Number 1-3, 1 being most important.

- ☐ **Housing**
- ☐ **Medical/dental services**
- ☐ **Religious services**
- ☐ **Shower**
- ☐ **Educational opportunities**
- ☐ **Laundry services**
- ☐ **Recreational facilities**
- ☐ **Ability to communicate with family/friends**
- ☐ **PX facilities**
- ☐ **Food Services**
- ☐ **Entertainment**

Other (please specify)

4. Please answer the following about your living quarters

	Not Satisfied	Sort of Satisfied	Satisfied	Extremely Satisfied	N/A
How satisfied were you with your living quarters?	☐	☐	☐	☐	☐
How satisfied were you with the safety?	☐	☐	☐	☐	☐
How satisfied were you with the privacy?	☐	☐	☐	☐	☐
How satisfied were you with the space available?	☐	☐	☐	☐	☐
How satisfied were you with the air conditioning?	☐	☐	☐	☐	☐
How satisfied were you with the utilities available (electricity/water)?	☐	☐	☐	☐	☐
The distance from the latrine from your room	☐	☐	☐	☐	☐

5. For all items in question 4 that you rated "Not satisfied" or "N/A", please tell us why you feel that way and any suggestions to improve it.

APPENDIX D: SURVEY (CONT)

6. During sandstorms, did sand get in?

- [ ] Yes
- [ ] No
- [ ] N/A

If yes, was it a lot or a little?

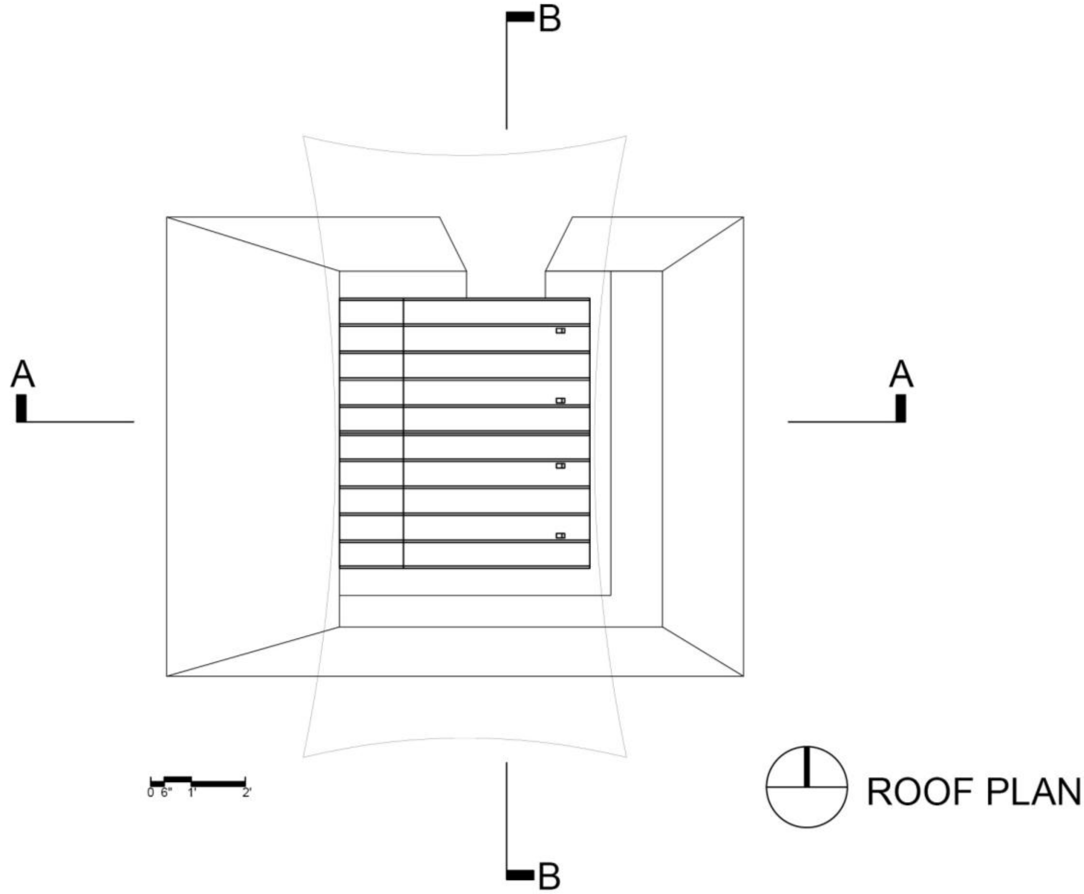
7. Were bugs/insects/rodents able to get into your room?

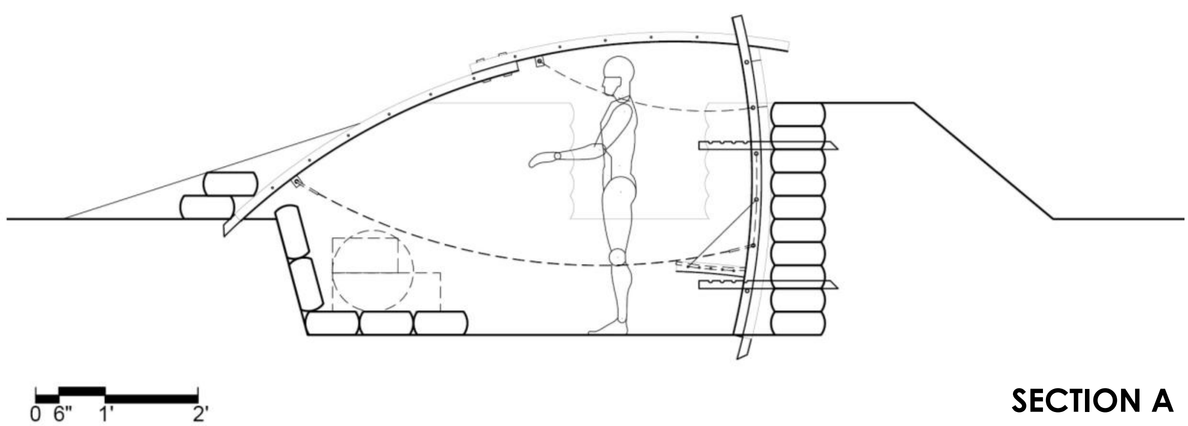
- [ ] Yes
- [ ] No

8. If you could improve 1 thing in your room, what would you have improved?

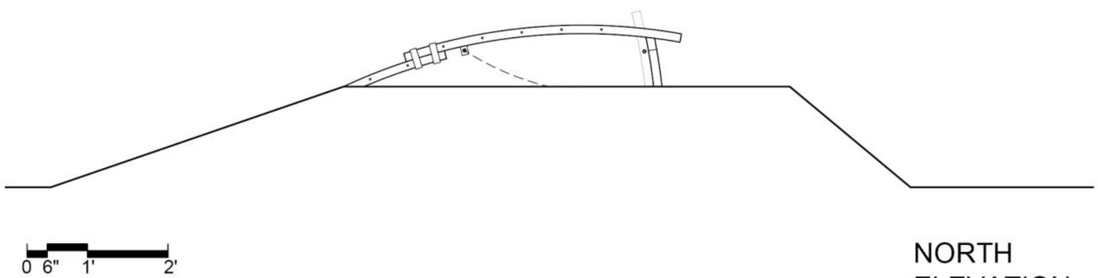
9. If you were in charge of the camp, what 3 facilities would you have for the camp to improve your life style?

APPENDIX E: DRAWINGS

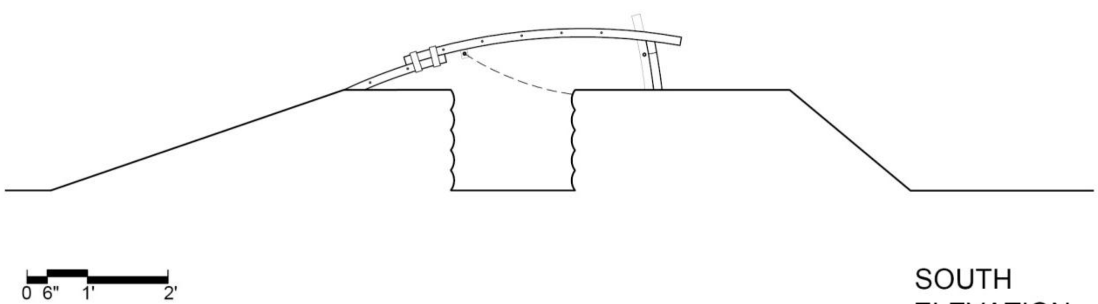




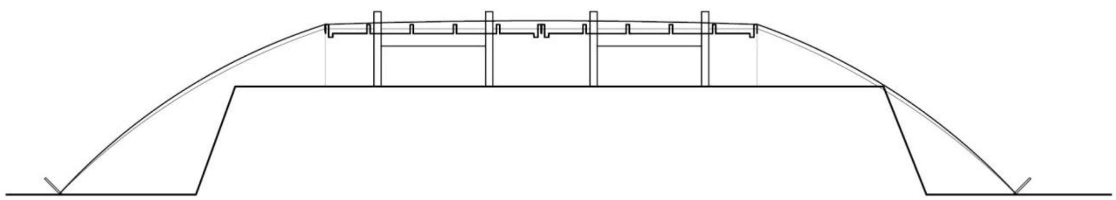
SECTION A



NORTH
ELEVATION

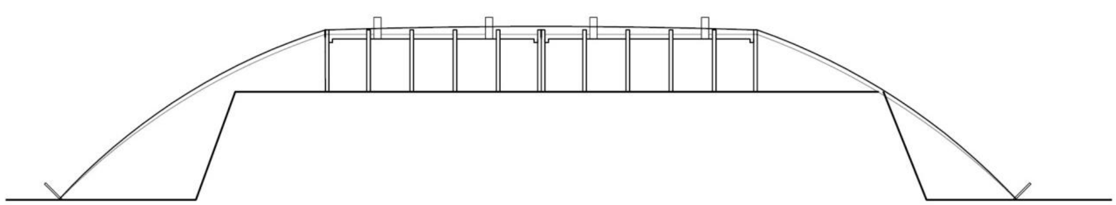


SOUTH
ELEVATION



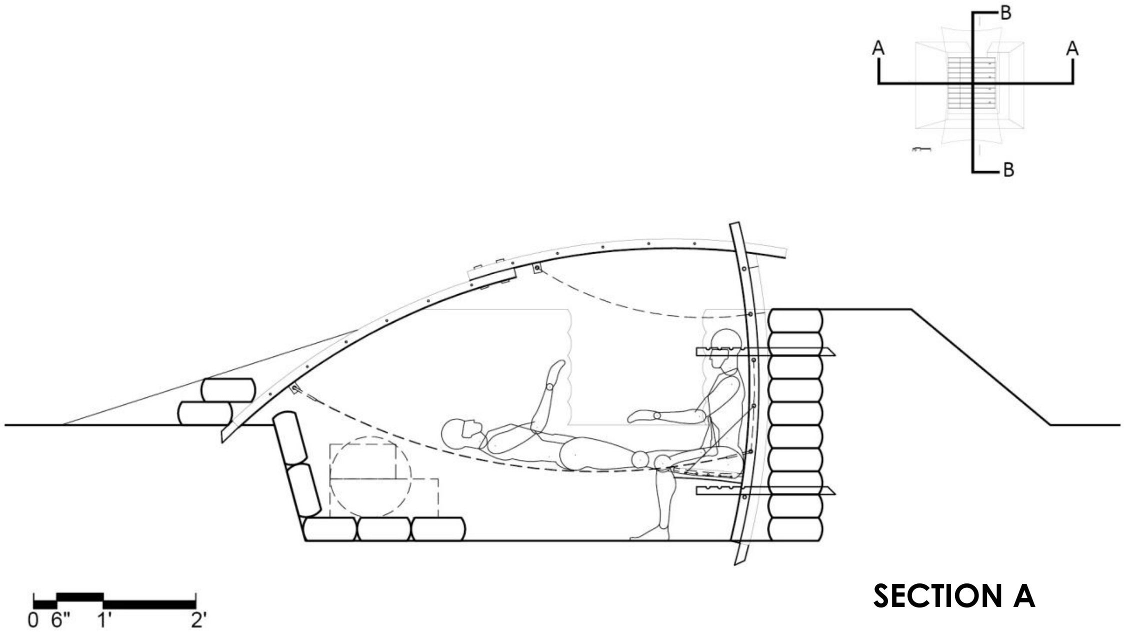
0 6" 1' 2'

EAST
ELEVATION

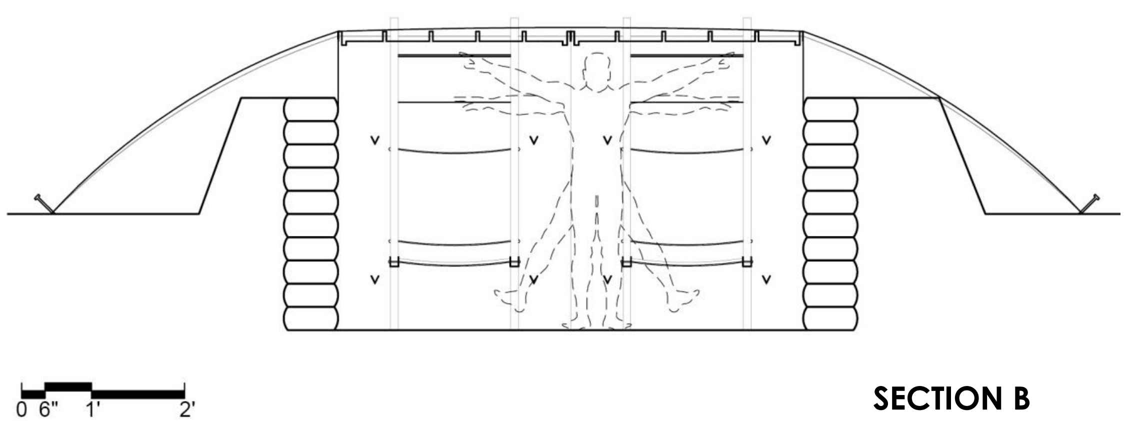


0 6" 1' 2'

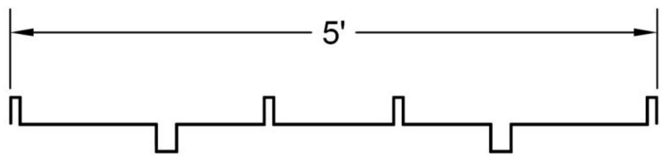
WEST
ELEVATION



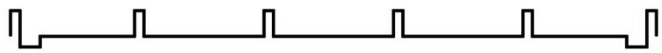
SECTION A

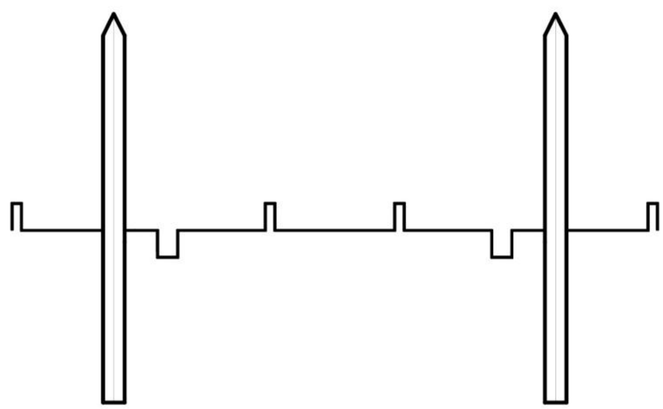


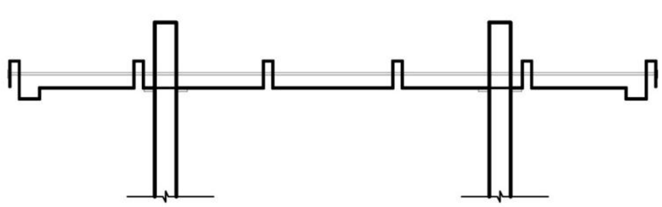
SECTION B



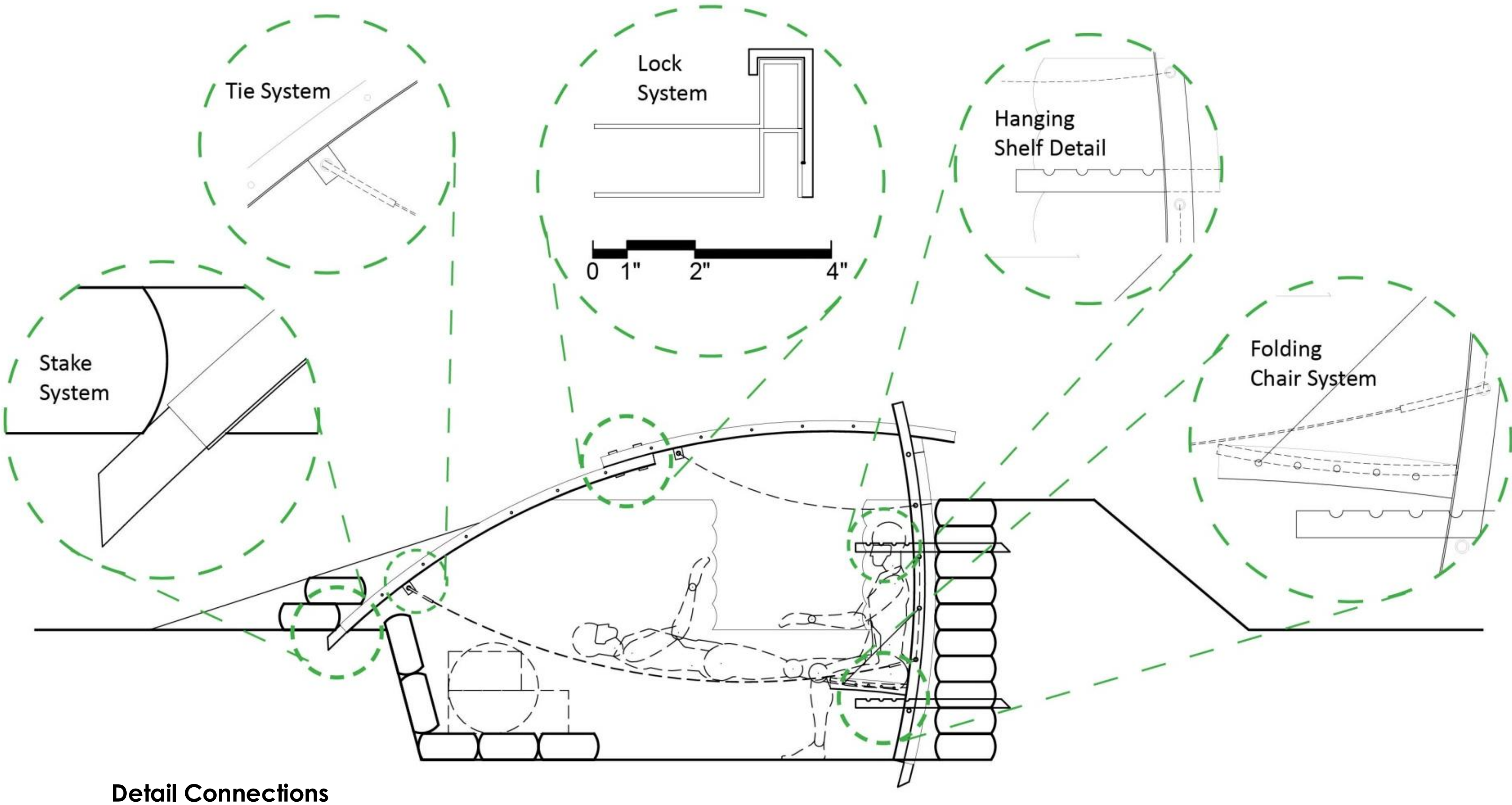
PANEL A


PANEL B


WALL SECTION

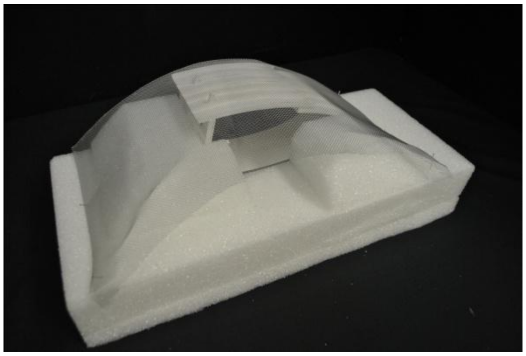

ROOF SECTION

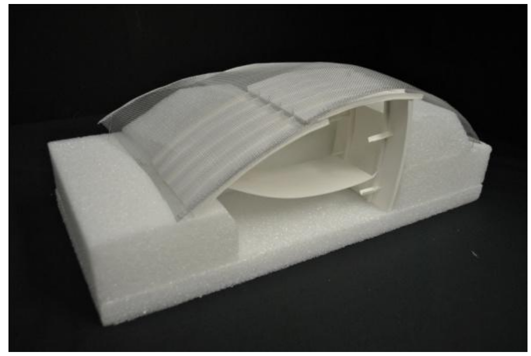
Details & Sections

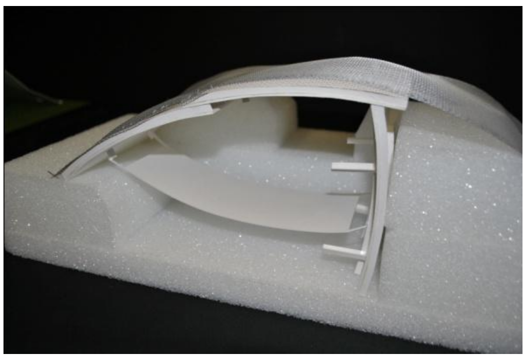

Tie System
Lock
System
0 1" 2" 4"
Hanging
Shelf Detail
Stake
System
Folding
Chair System
Detail Connections
0 6" 1' 2'

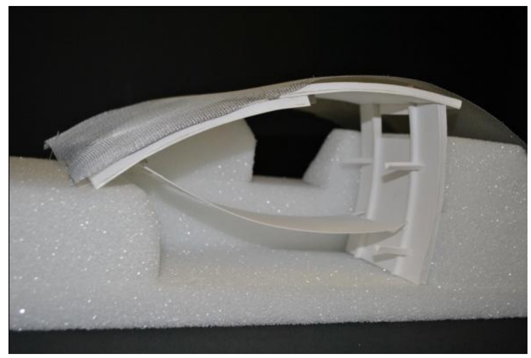
SECTION A

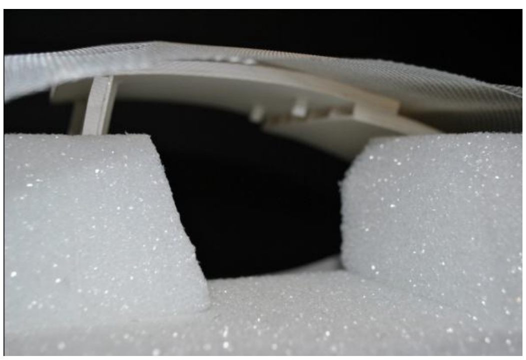
APPENDIX F: FINAL SECTION MODEL

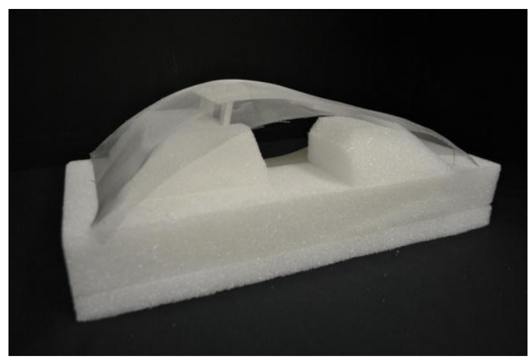


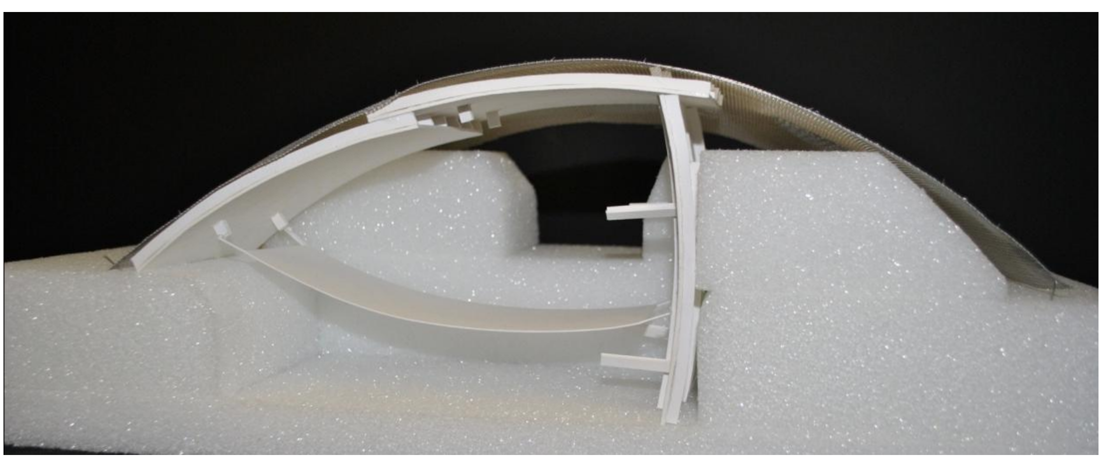




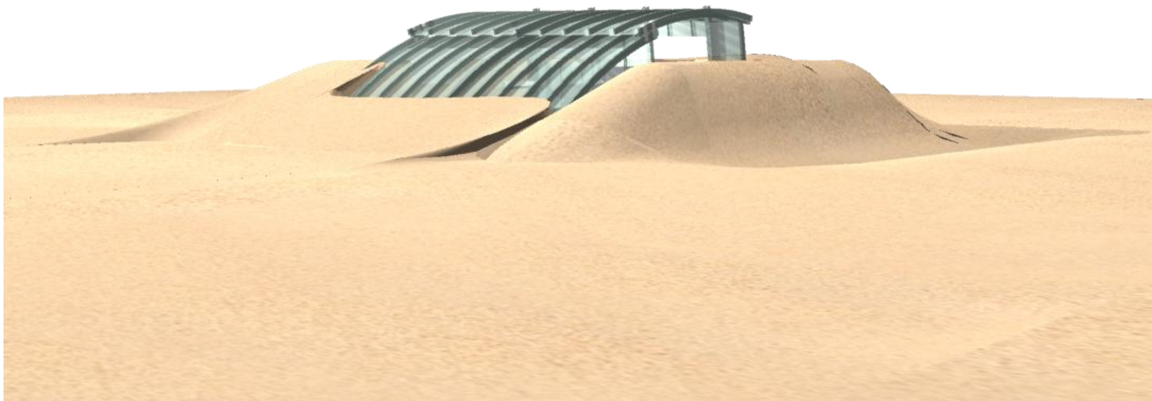




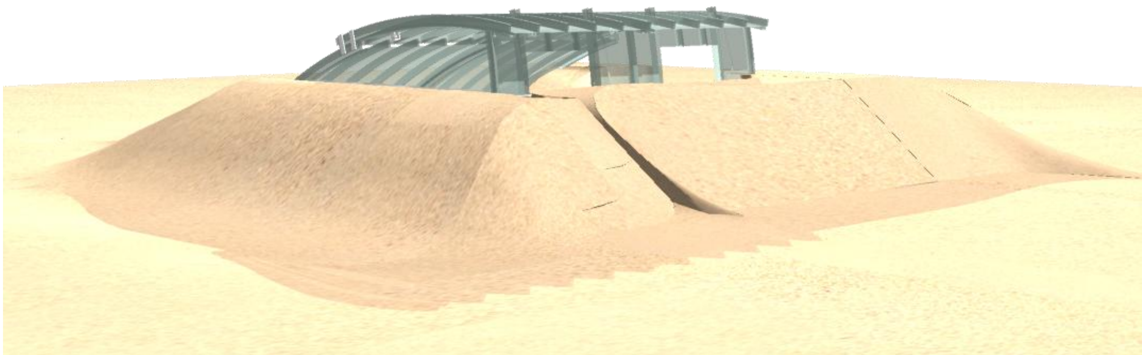




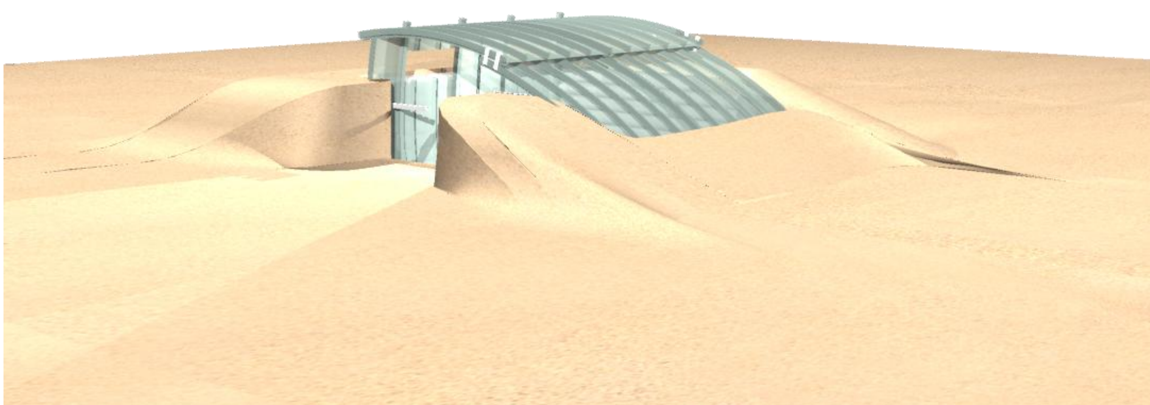
APPENDIX G: RENDERINGS



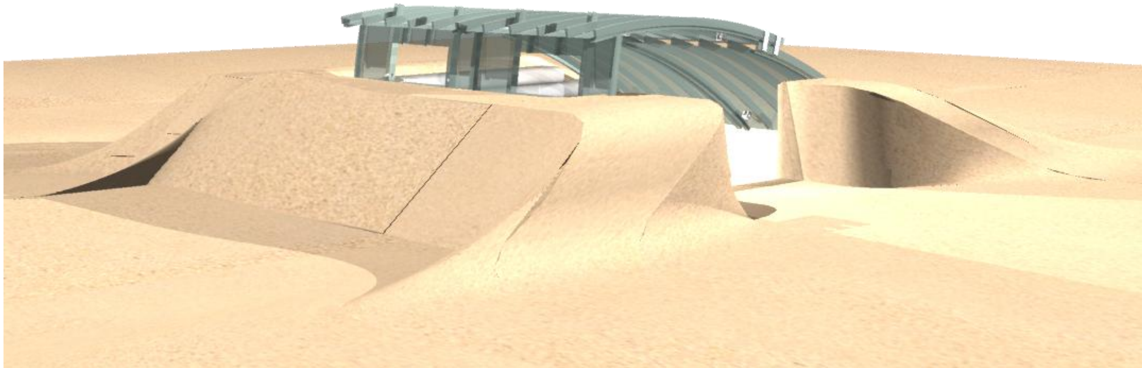
View of the Back



View of the Front



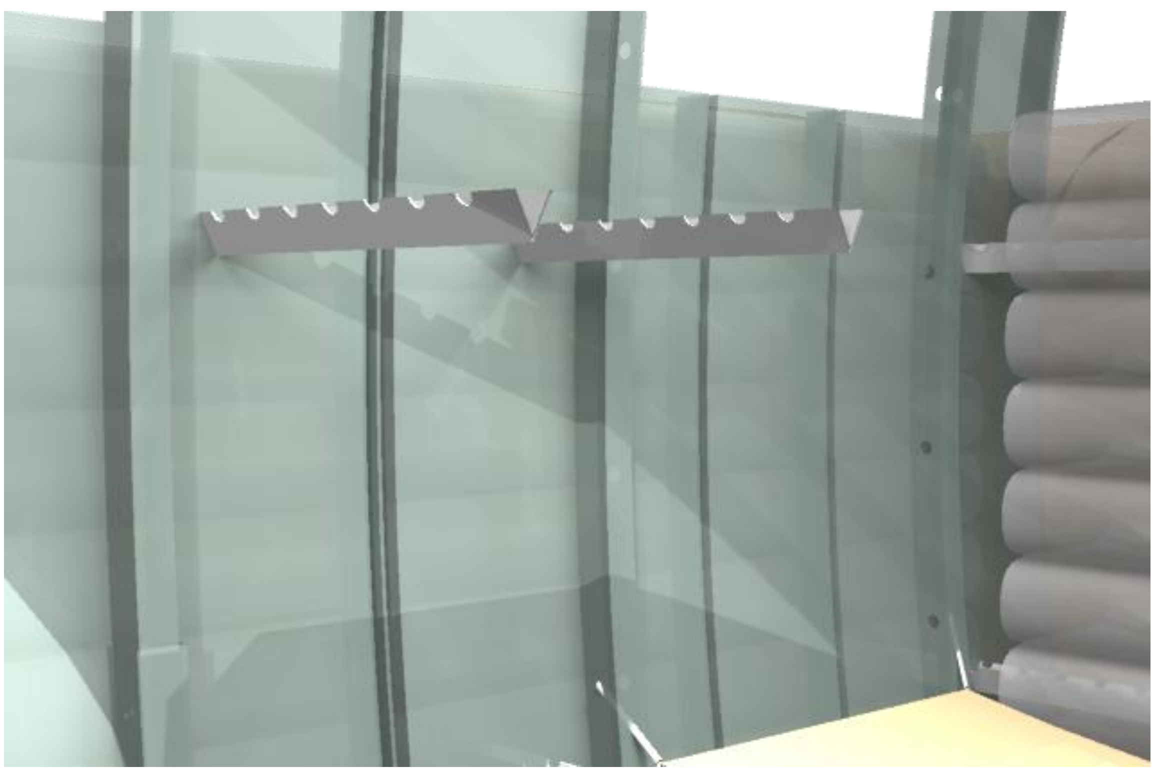
View of Entry



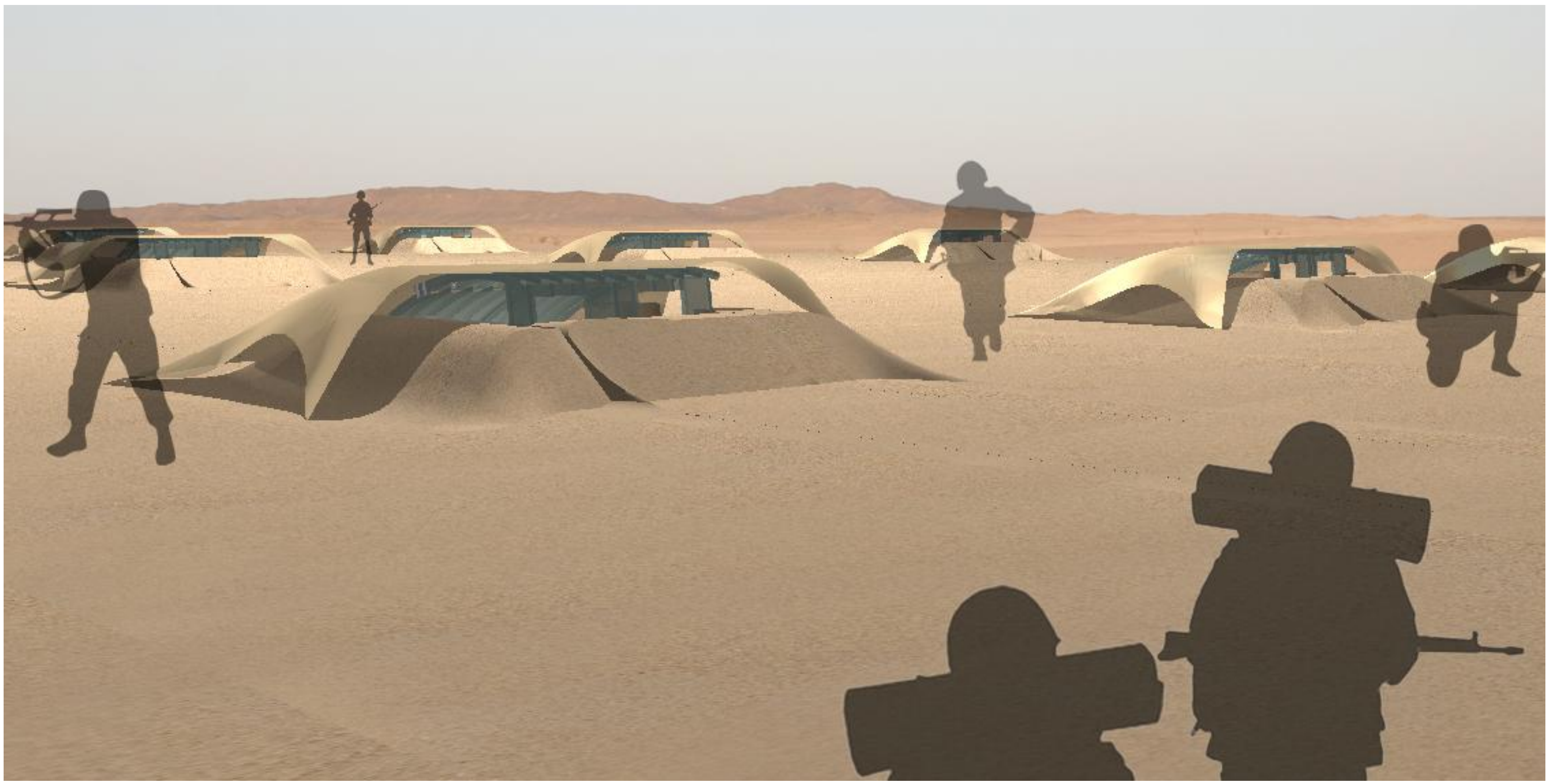
View of Entry from the Front

Model with Canvas

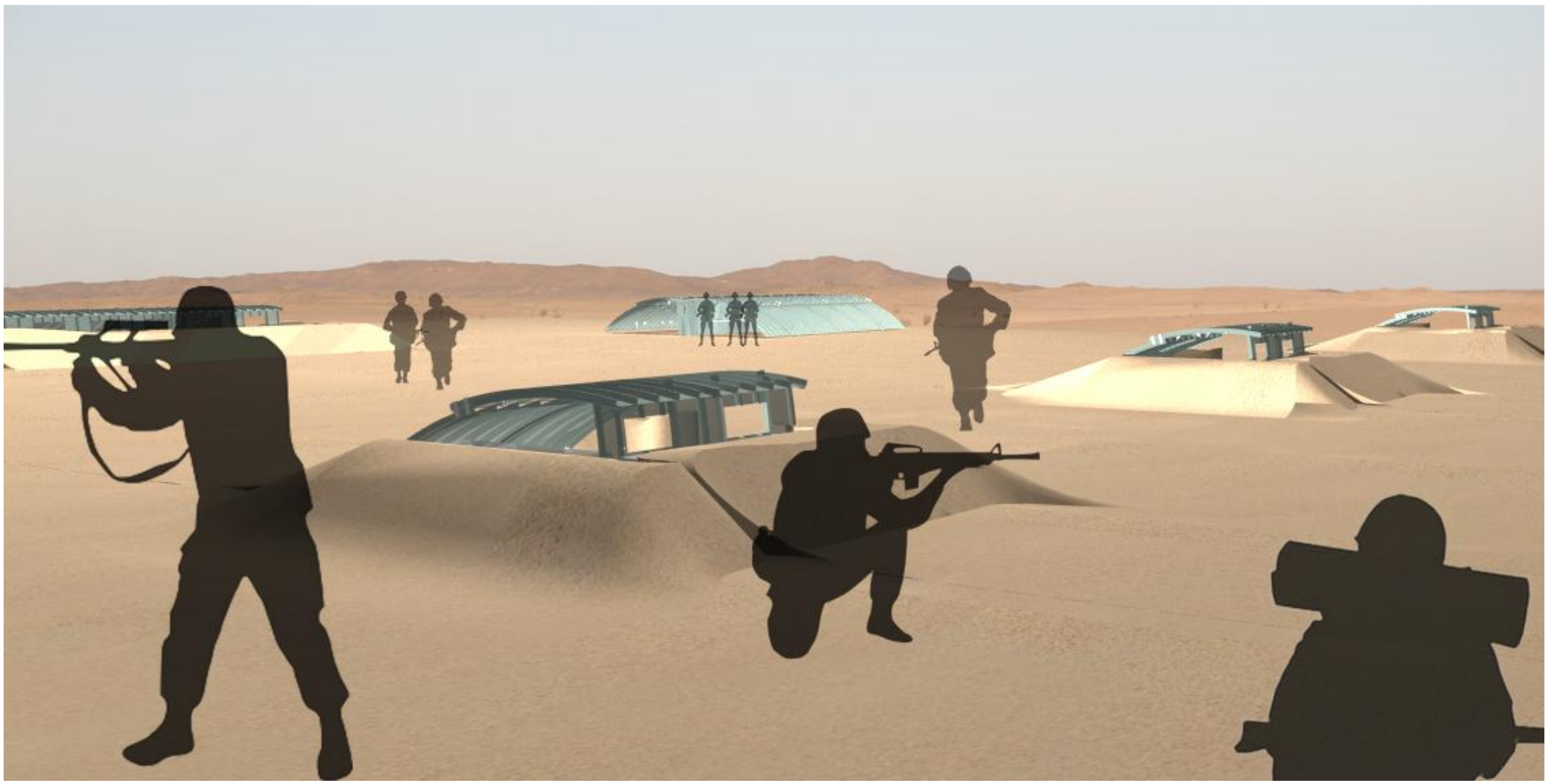
Close Up Render from Entry Point



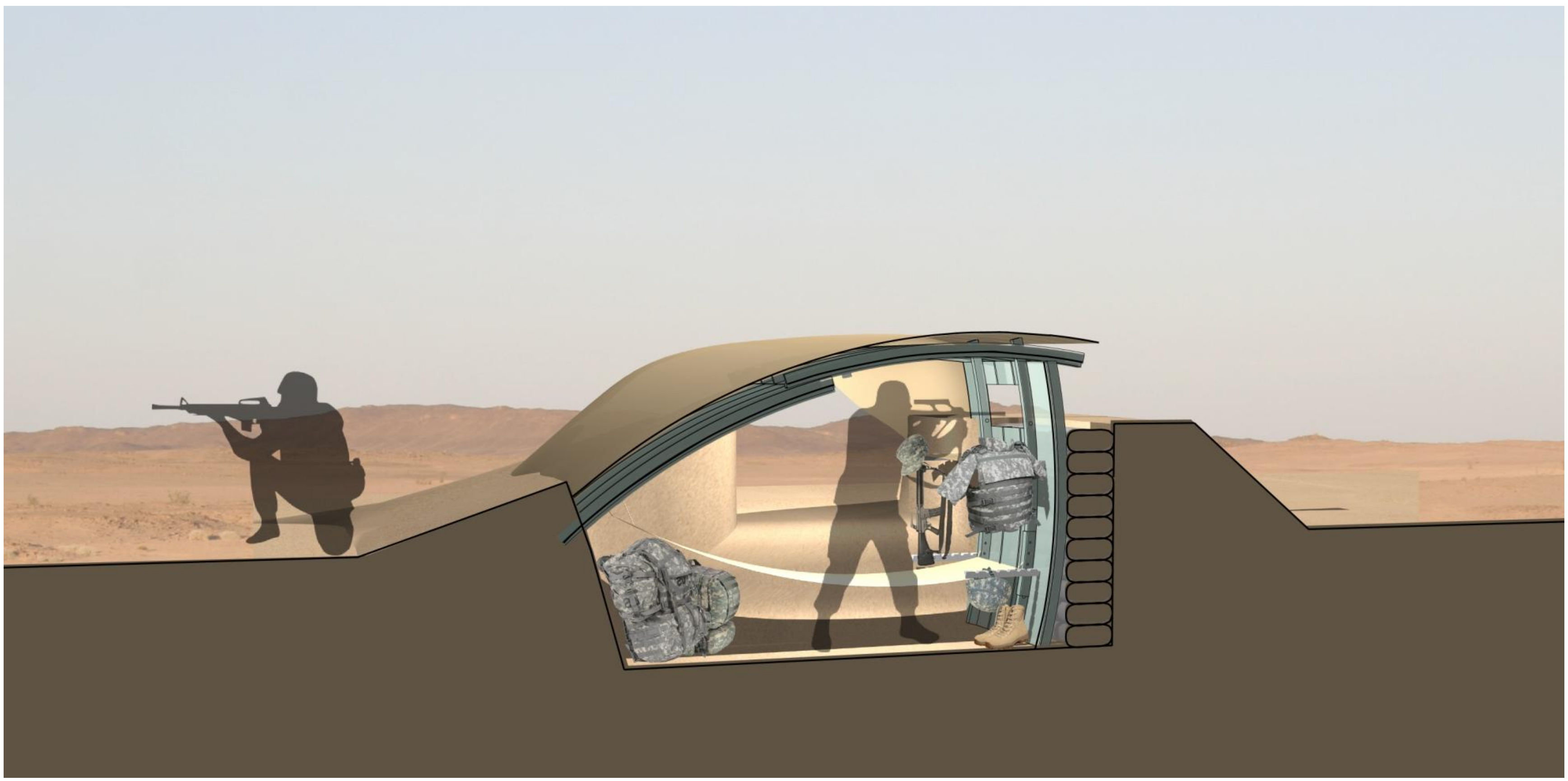
Detail Render of Hanger System



War Shelters Scenario 1: Multiple War Shelters of the same design model



War Shelters Scenario 2: Multiple War Shelters of different design model

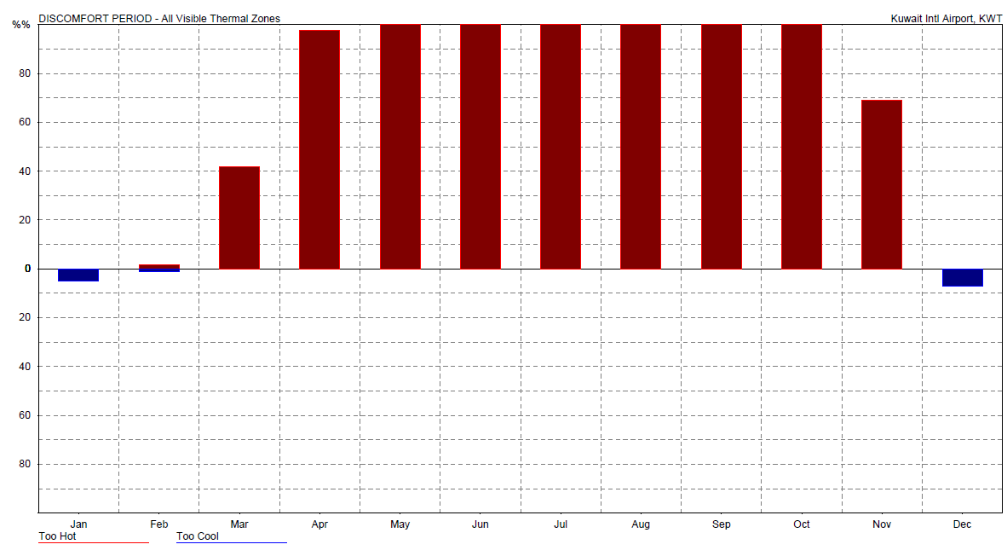


Rendered Section with personal equipment

APPENDIX H: THERMAL ANALYSIS DATA

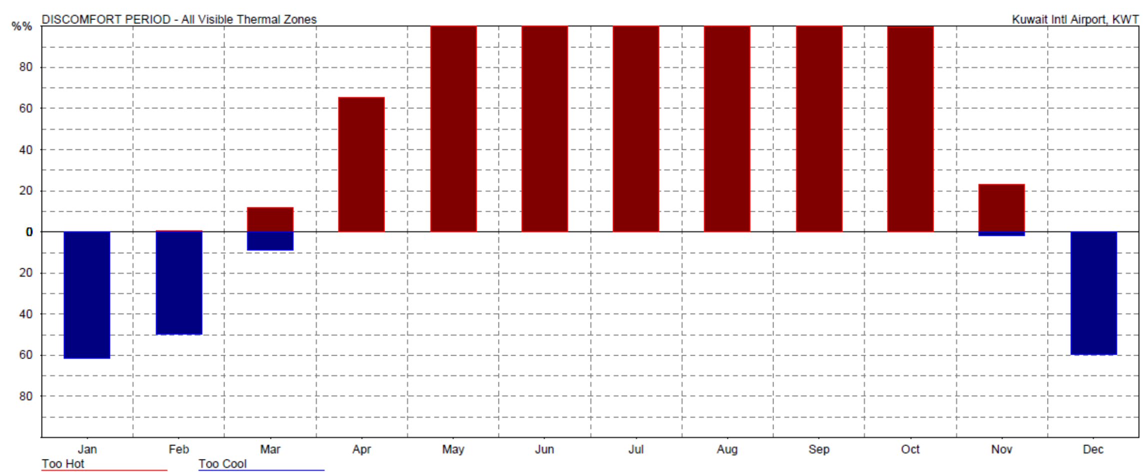
Case 1: CHU with Windows

DISCOMFORT PERIOD			
DISCOMFORT DEGREE HOURS			
All Visible Thermal Zones			
Comfort: Zonal Bands			
	TOO HOT	TOO COOL	TOTAL
MONTH	(%)	(%)	(%)
------	--------	---------	-------
Jan	0	4.84	4.84
Feb	1.64	1.34	2.98
Mar	41.8	0	41.8
Apr	97.64	0	97.64
May	100	0	100
Jun	100	0	100
Jul	100	0	100
Aug	100	0	100
Sep	100	0	100
Oct	100	0	100
Nov	69.03	0	69.03
Dec	0	7.26	7.26
------	--------	---------	-------
TOTAL	810.1	13.4	823.5



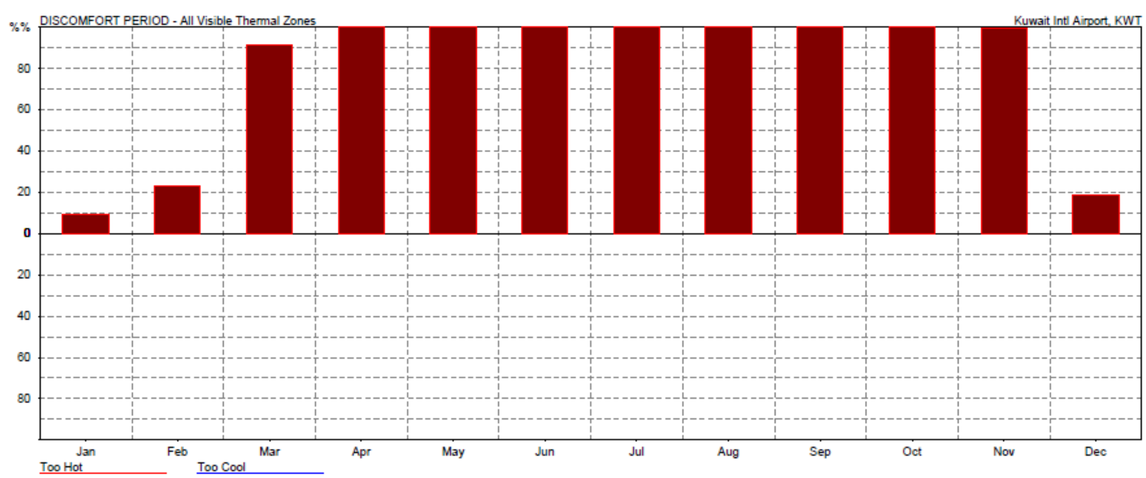
Case 2: CHU without Windows

DISCOMFORT PERIOD			
DISCOMFORT DEGREE HOURS			
All Visible Thermal Zones			
Comfort: Zonal Bands			
	TOO HOT	TOO COOL	TOTAL
MONTH	(%)	(%)	(%)
------	--------	---------	-------
Jan	0	61.56	61.56
Feb	0.45	50	50.45
Mar	11.56	8.87	20.43
Apr	65.42	0	65.42
May	100	0	100
Jun	100	0	100
Jul	100	0	100
Aug	100	0	100
Sep	100	0	100
Oct	99.46	0	99.46
Nov	22.92	1.67	24.58
Dec	0	59.81	59.81
------	--------	---------	-------
TOTAL	699.8	181.9	881.7



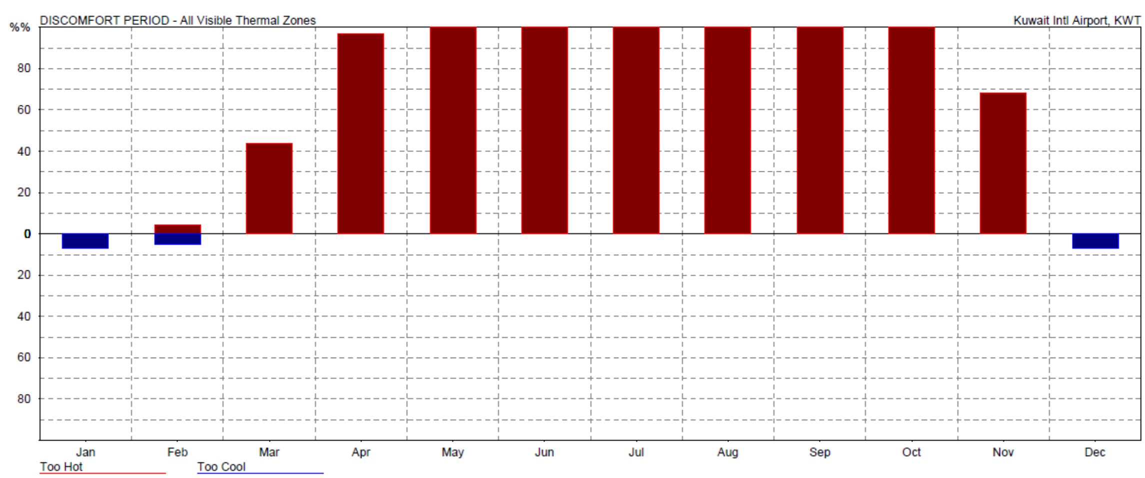
Case 3: Tent with Dead Air

DISCOMFORT PERIOD			
DISCOMFORT DEGREE HOURS			
All Visible Thermal Zones			
Comfort: Zonal Bands			
	TOO HOT	TOO COOL	TOTAL
MONTH	(%)	(%)	(%)
------	--------	---------	-------
Jan	9.27	0	9.27
Feb	22.92	0	22.92
Mar	91.26	0	91.26
Apr	100	0	100
May	100	0	100
Jun	100	0	100
Jul	100	0	100
Aug	100	0	100
Sep	100	0	100
Oct	100	0	100
Nov	99.17	0	99.17
Dec	18.55	0	18.55
------	--------	---------	-------
TOTAL	941.2	0	941.2



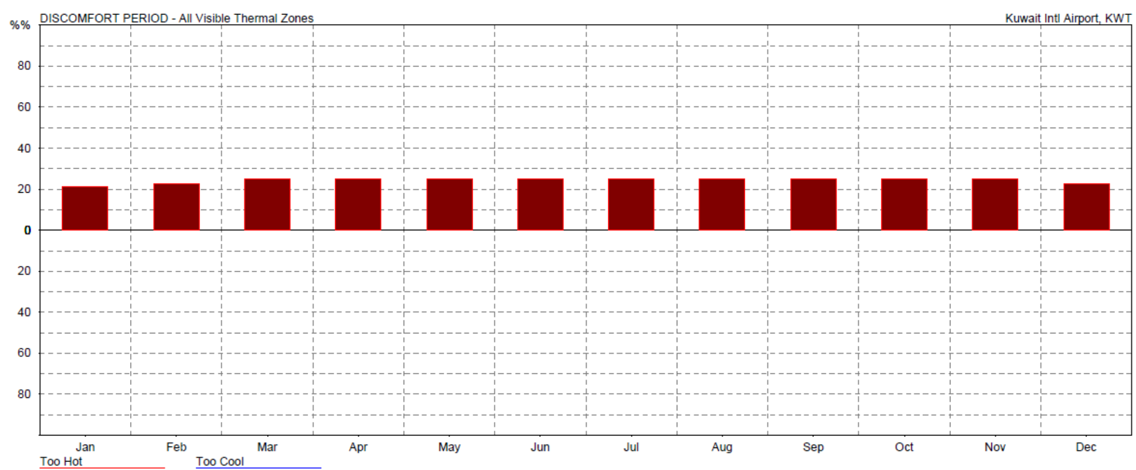
Case 4: Tent with no Dead Air

DISCOMFORT PERIOD			
DISCOMFORT DEGREE HOURS			
All Visible Thermal Zones			
Comfort: Zonal Bands			
	TOO HOT	TOO COOL	TOTAL
MONTH	(%)	(%)	(%)
------	--------	---------	-------
Jan	0.13	6.99	7.12
Feb	4.46	5.06	9.52
Mar	43.68	0	43.68
Apr	96.67	0	96.67
May	100	0	100
Jun	100	0	100
Jul	100	0	100
Aug	100	0	100
Sep	100	0	100
Oct	100	0	100
Nov	68.19	0	68.19
Dec	0	7.12	7.12
------	--------	---------	-------
TOTAL	813.1	19.2	832.3

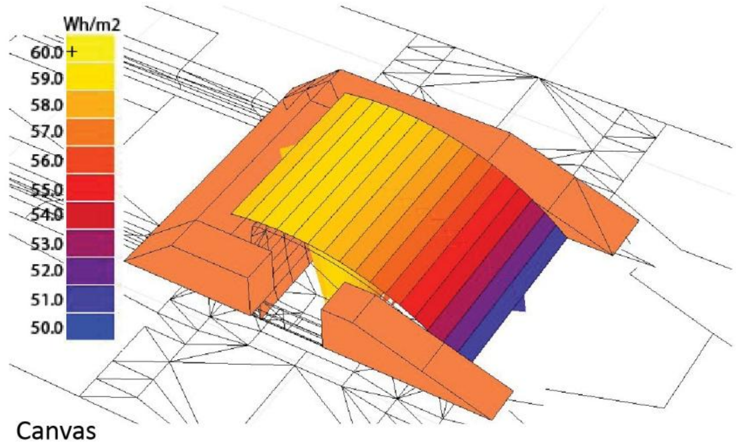


Case 4: Design Example with Steel and Canvas

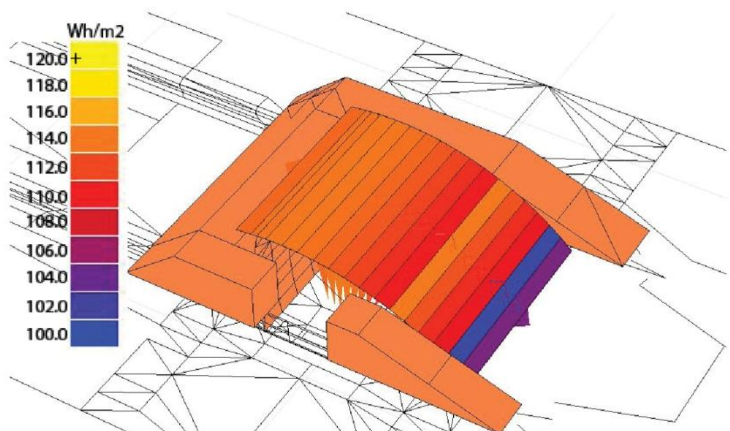
DISCOMFORT PERIOD			
DISCOMFORT DEGREE HOURS			
All Visible Thermal Zones			
Comfort: Zonal Bands			
	TOO HOT	TOO COOL	TOTAL
MONTH	(%)	(%)	(%)
------	--------	---------	------
Jan	21.24	0	21.24
Feb	22.81	0	22.81
Mar	25	0	25
Apr	25	0	25
May	25	0	25
Jun	25	0	25
Jul	25	0	25
Aug	25	0	25
Sep	25	0	25
Oct	25	0	25
Nov	25	0	25
Dec	22.65	0	22.65
------	--------	---------	------
TOTAL	291.7	0	291.7



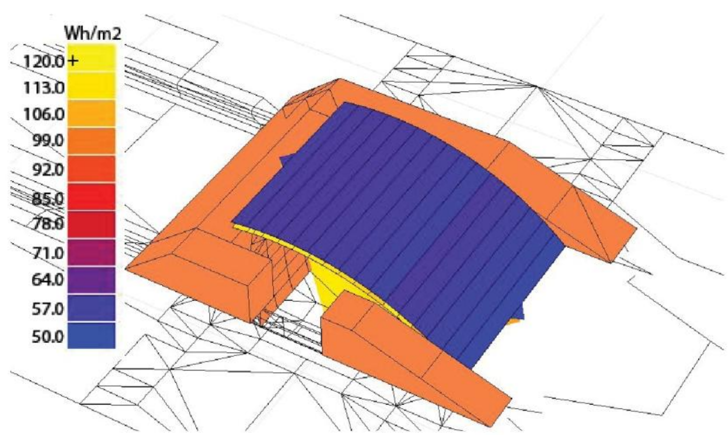
APPENDIX I: SOLAR RADIATION DATA



Canvas



Corrugated Metal

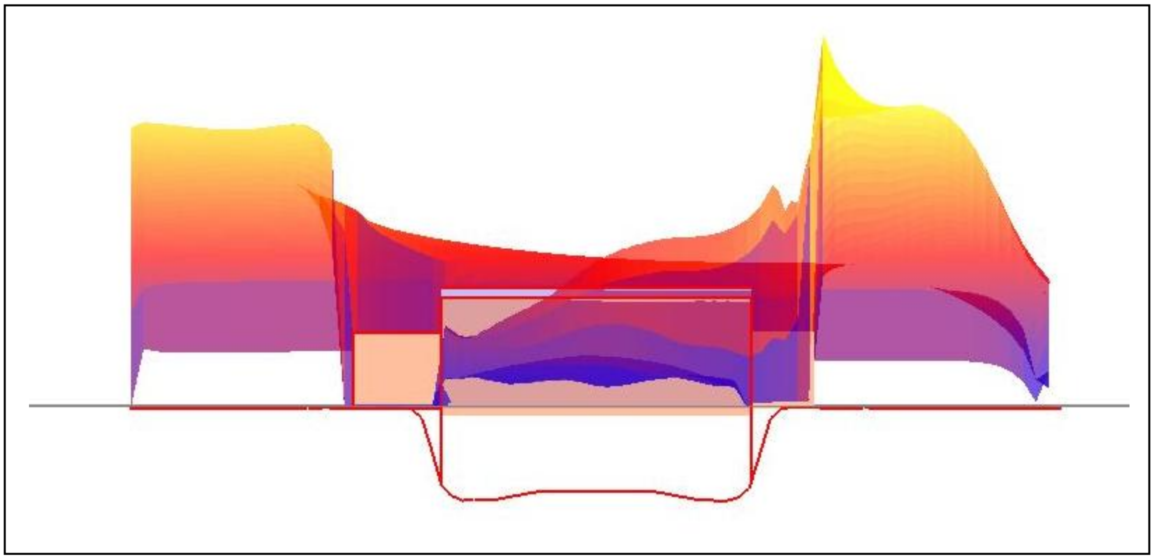


Corrugated Metal + Canvas

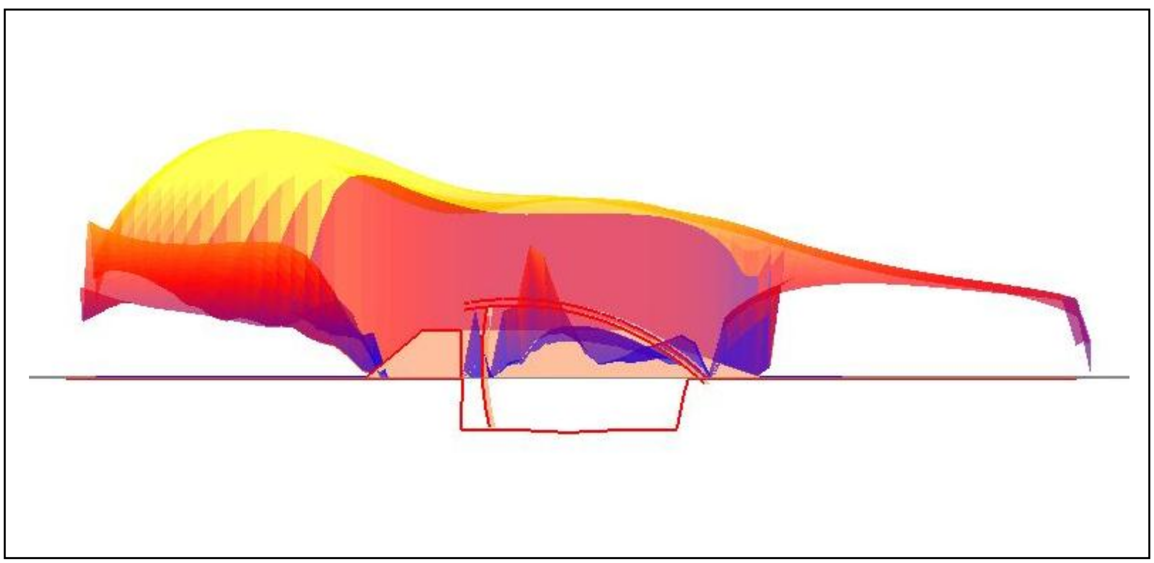
APPENDIX J: COMPUTATIONAL FLUID DYNAMIC RESULTS

Air Flow Rate Sections

Below are two sections taken from the midpoint of each side to illustrate the dynamics of the airflow rate within the space.



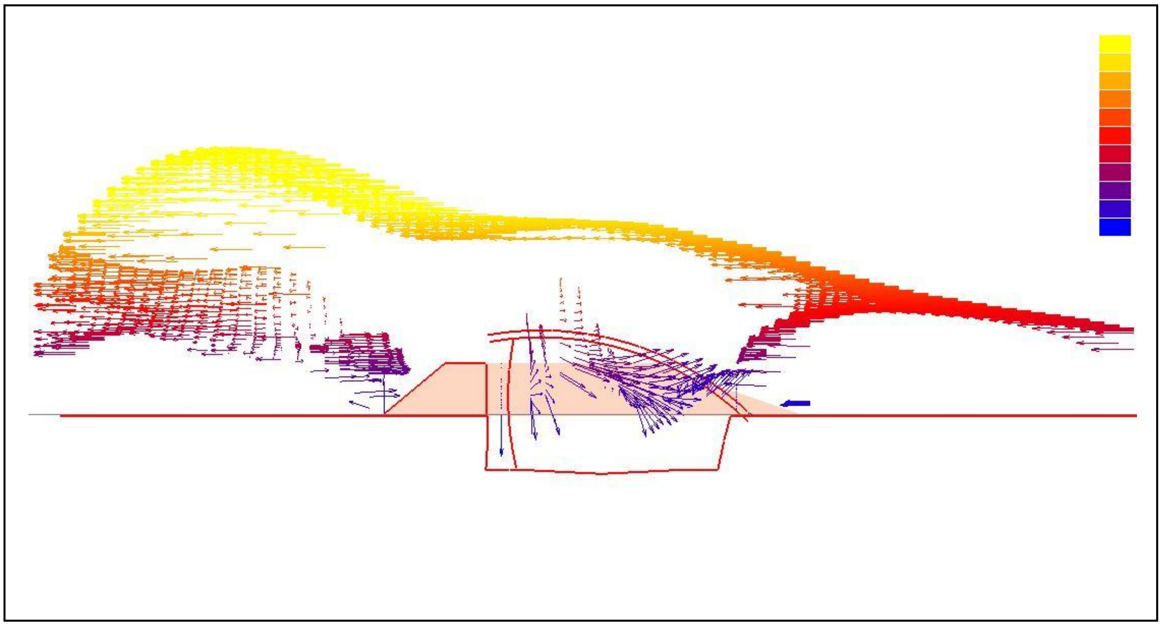
Air Flow Rate- Cross Section



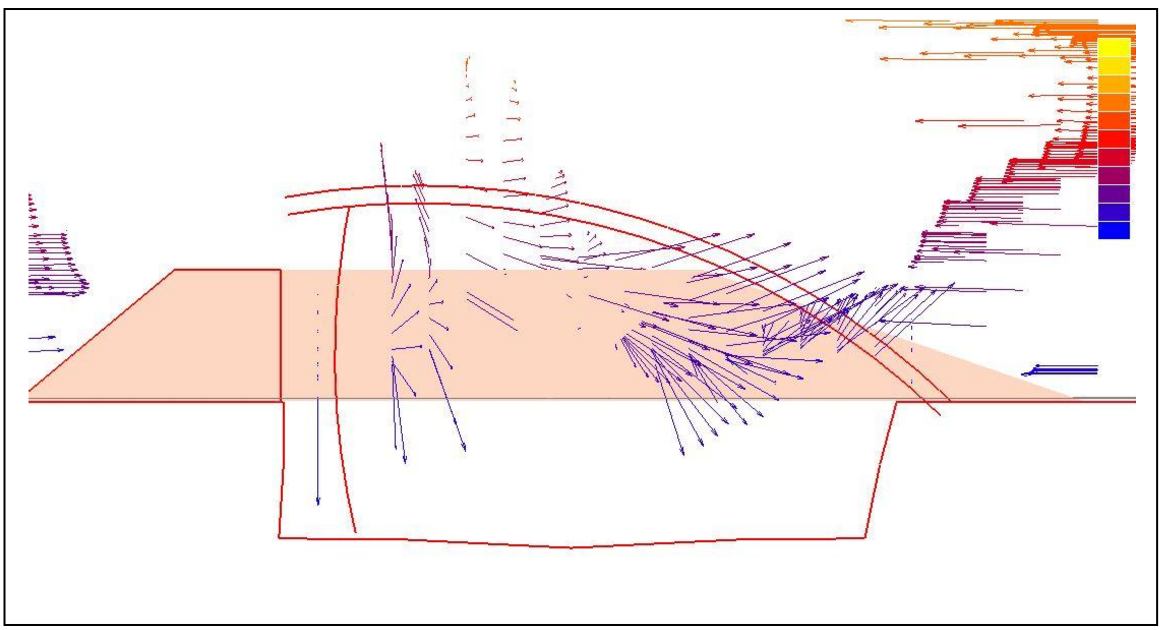
Air Flow Rate- Longitudinal Section

Air Flow Vector-Longitudinal Section

Below are four sections taken from the midpoint of each side to illustrate the airflow.

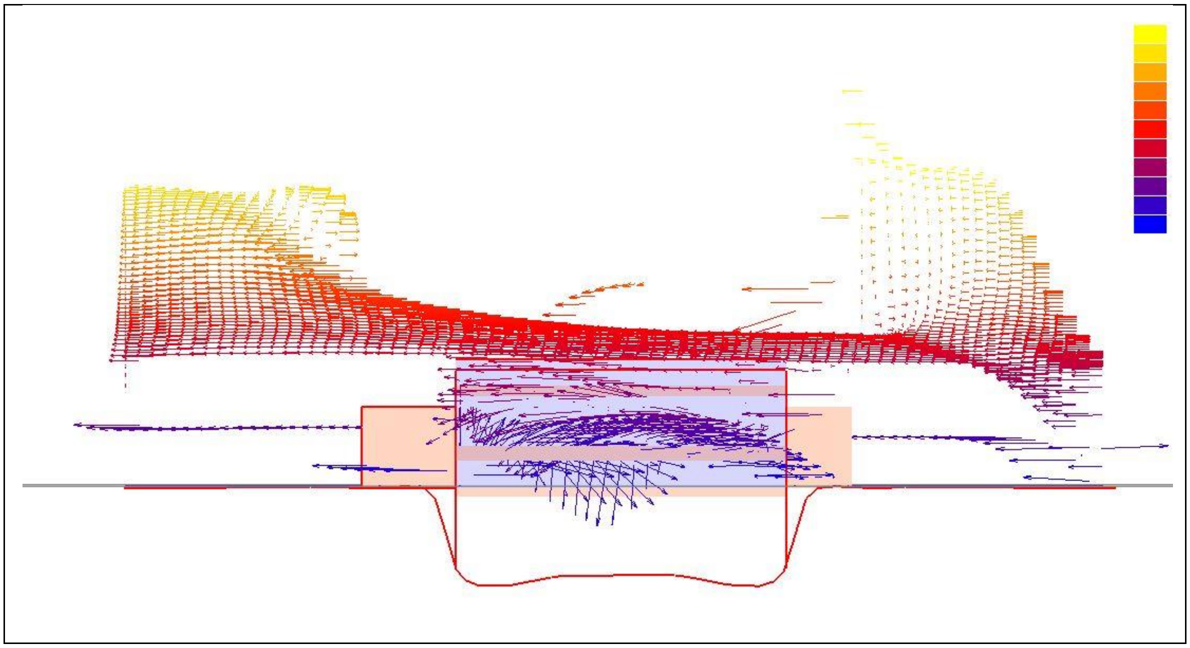


Air Flow Vector- Longitudinal Section

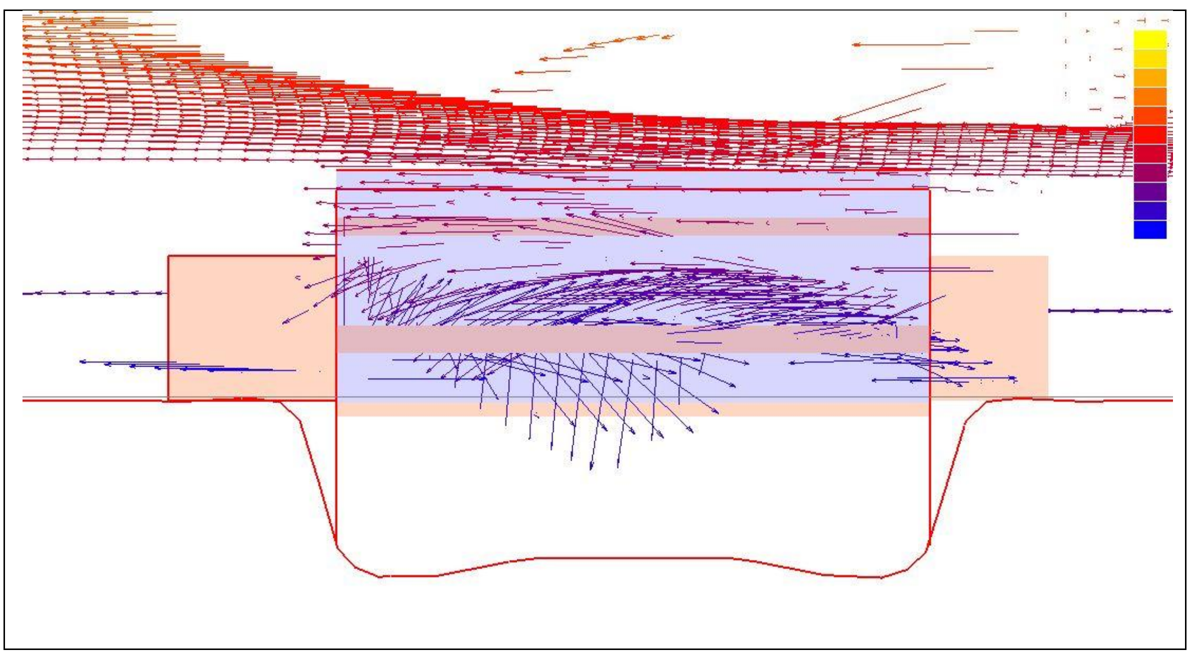


Air Flow Vector-Close Up

Air Flow Vector-Cross Section



Air Flow Vector: Cross Section-Close Up



Air Flow Vector: Cross Section-Close Up

LIST OF ABBREVIATIONS

ACH	Aircraft Hangers
CHU	Containerized Housing Unit
CLS	Contractor Logistics Support
COL	Contingency Operation Base
COL	Contingency Operation Location
CONEX	Container Express
COS	Contingency Operation Sites
DRASH	Deployable Rapid Assembly Shelter
ESC	Expandable Shelter Containers
FM	Field Manual
FOB	Forward Operating Base
FOB	Forward Operating Base
GP	General Purpose
GS	General Schedule
HQUSACE	Headquarters of US Army Corps of Engineers
ICS	Individual Combat Shelter
ISO	International Organization for Standardization
MGPTS	Modular General Purpose Tent System
MOB	Main Operating Base
MSS	Medium Shelter System
OACSIM	Office of the Assistant Chief of Staff for Installation Management
OEF	Operation of Enduring Freedom
OIF	Operation of Iraqi Freedom
PX	Post Exchange
SEA	Southeast Asia
TEMPER	Tent, Extendable Modular Personnel
UA	Unit Action
UFS	Universal Fabric Structure
USAREUR	United States Army Europe

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Figure 2: "Architecture 2030: Why?." Architecture 2030. http://architecture2030.org/the_problem/buildings_problem_why (accessed April 1, 2010).

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Figure 10: " Historical Vignette 074 - Army Engineers Oversaw Military Reconstruction in Post-WWII Occupied Japan ." US Army Corps of Engineers - HQ . http://www.usace.army.mil/History/hv/Pages/074-Japan_Post_WWII.aspx (accessed April 1, 2010).

Figure 11: "|| SUBLIME || K-span Structures installation." || SUBLIME || Home. http://www.sclsc.com/42-0-K-span+Structures+installation.html (accessed April 5, 2010).

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Figure 16: Shao Yu Lin- Author

Figure 17: Steadman, Philip. *The Evolution of Designs: Biological Analogy in Architecture and the Applied Arts*. New York: Routledge, 2008.

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Figure 32: Areole Diagram

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